massport
Massachusetts Port Authority
One Harborside Drive. Suite 200S
East Boston, MA 02128-2909
Telephone (617) 568-5000
www.massport.com

March 11, 2019

VIA EMAIL AND FIRST CLASS MAIL
Lucas Smolcic Larson
MuckRock News
DEPT MR 61821
411 A Highland Ave
Somerville, MA 02144
61821-70966920@requests.muckrock.com

Re: Public Records Request-SRP 18/644 and SPR 18/2060

Dear Mr. Larson:

This is a follow-up to your public records request to the Massachusetts Port Authority (the "Authority" or "Massport") for a copy of Massport's Disaster and Infrastructure Resiliency Plan (DRIP).

Enclosed, please find a redacted copy of the DRIP. The Authority redacted information that details the Authority's critical assets and provides a vulnerability assessment of those assets (chapter 5 &6), pursuant to M.G.L. c. 4 §7(26)(a) and (n).

Sincerely,

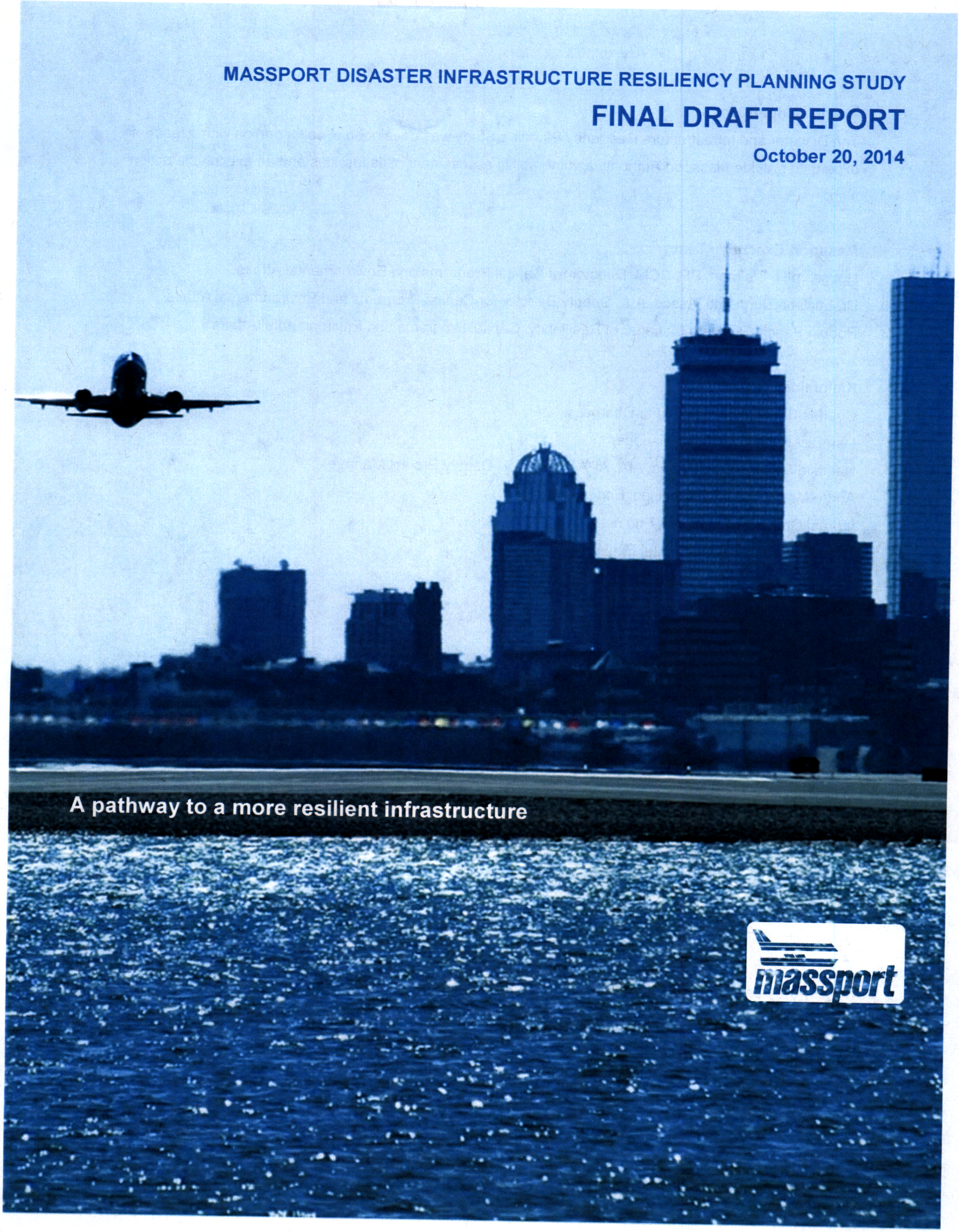
Ashley K. Carvalho
Senior Legal Counsel

cc: Angela Puccini, Office of the Secretary of the Commonwealth

MASSPORT DISASTER INFRASTRUCTURE RESILIENCY PLANNING STUDY

FINAL DRAFT REPORT

October 20, 2014



A pathway to a more resilient infrastructure

massport

Acknowledgements

The Disaster and Infrastructure Resiliency Planning Study was developed in collaboration with a team of experts to provide Massport Authority a vulnerability assessment of its facilities and an executable action plan.

Massport Executive Team

Houssam H. Sleiman, PE, CCM, Director for Capital Programs and Environmental Affairs

Dr. Luciana Burdi, Intl. Assoc. AIA, Deputy Director for Capital Programs and Environmental Affairs

Robbin Peach, Program Manager of Resiliency, Capital Programs and Environmental Affairs

Kleinfelder Team

Charles Sacre, PE, Principal-in-Charge

Lisa Dickson, PG, Project Manager

Nathalie Beauvais Int'l Assoc. AIA, APA, LEED AP, Deputy Project Manager

Andre Martecchini, PE, Principal Engineer

Indrani Ghosh, PhD, Project Engineer

Nasser Brahim, Environmental Expertise

Alexander Otenti, PE, Project Engineer

Vijaylaxsmi Kesavan, Environmental Expertise

Daniel Fraser, Financial Manager

Subject Matter Experts/ Advisors to Kleinfelder

Katharine Hayhoe, PhD, ATMOS Research and Consulting

Paul Kirshen, PhD, University of New Hampshire

Ellen Douglas PhD, University of Massachusetts, Boston

Kirk Bosma, PE, Woods Hole Group

Stephen Flynn, PhD and Peter Boynton, Kostas Research Institute for Homeland Security, Northeastern University

Jerome Hajjar, PhD, PE, Northeastern University

VJ Associates of New England

Architectural Engineers Inc.

Massport Resiliency Working Group and Capital Programs Team

The project team would like to acknowledge the numerous Massport staff who shared their time and knowledge and assisted in the identification of critical assets, organization of site visits, and review of proposed recommendations. Their contributions were indispensable to the process and its outcomes.

TABLE OF CONTENTS

LIST OF TABLES & FIGURES

TABLES

FIGURES

1. EXECUTIVE SUMMARY

Resiliency is the ability of a system to withstand a major disruption within acceptable degradation parameters, recover within an acceptable time, and balance composite costs and risks.

Purpose of Study

Recent extreme weather events, such as Hurricanes Sandy, Irene and the winter storm Nemo, have created a keen focus on the link between climate and the resiliency of the built environment. Logan International Airport and the maritime facilities in South Boston are highly susceptible to sea level rise and storm surge impacts associated with climate change. The Massachusetts Port Authority (Massport) has recognized this risk and launched a comprehensive resiliency initiative related to ensuring business continuity in the midst of various human and natural risks. This report focuses on the risks associated with extreme weather events and climate change. It includes a hazards analysis, a vulnerability assessment, and resiliency recommendations for both near-term and longer-term capital improvements.

This Disaster and Infrastructure Resiliency Planning Study (DIRP) is a key component of the Logan Airport Sustainability Management Plan (SMP), since it was identified as a focus area for the SMP. The baseline information and recommendations identified in the DIRP study will be incorporated into the SMP as a chapter. The FAA is supportive of including climate adaptation and resiliency planning in the broad reach of considerations in sustainability planning. The Logan SMP includes a greenhouse gas (GHG) focus area, and develops goals, objectives and initiatives for reducing GHG. The resiliency section will provide strategies for addressing the impacts of GHG and climate change and for making infrastructure at Logan Airport and the maritime facilities in South Boston more sustainable and resilient.

The Study Area and Focus

The core study area encompasses Logan Airport and the maritime facilities in South Boston, although flooding simulations and design guidelines also include Massport's other holdings in South Boston and East Boston. Detailed facility reports and recommendations were prepared for assets that were identified as being critical to the operation and recovery of the airport and maritime facilities both during and immediately following an extreme flooding event. The list and

ranking of critical assets were developed in coordination with key Massport stakeholders, Northeastern University's Kostas Institute on Homeland Security and ultimately approved by the Director for Capital Programs and Environmental Affairs.

Identifying the Hazard

The hazard analysis focused on sea level rise and storm surge flooding, both for the immediate future, as well as 20 years into the future. Design flood elevations were determined based on an understanding of past events and projected changes in sea level rise and storm intensities. Leading climate experts, including Dr. Katharine Hayhoe, Dr. Paul Kirshen, Dr. Ellen Douglas and Kirk Bosma, P.E., were engaged in these discussions and, although this particular study focuses on sea level rise and storm surge, Dr. Hayhoe also provided downscaled projections for temperature and precipitation that can be leveraged for subsequent Massport analyses. SLOSH modeling was conducted to simulate the extent and depth of flooding for various storm scenarios at both Logan Airport and the maritime facilities in South Boston. The results of the model runs for a Category 2 hurricane hitting at mean high high water (MHHW) for the maritime facilities at South Boston and at Logan Airport are shown in Figures 1 and 2, respectively.

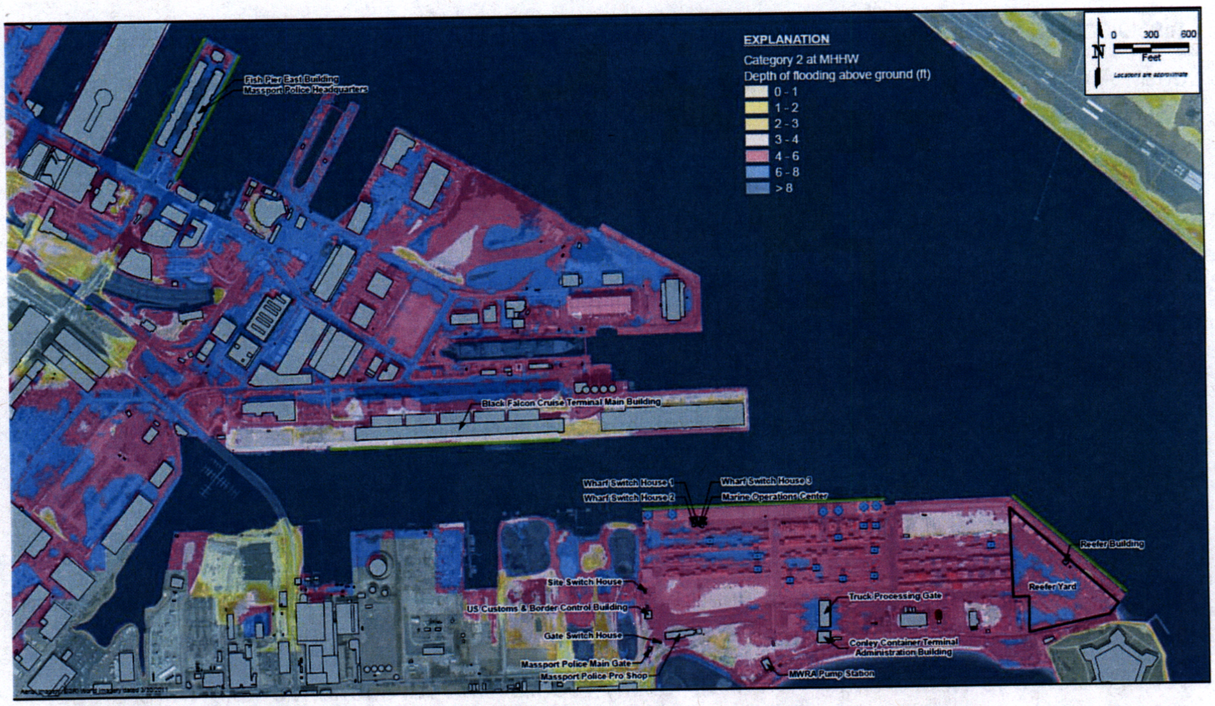


Figure 1 - Results of Category 2 Hurricane Hitting at MHHW – Maritime Facilities in South Boston

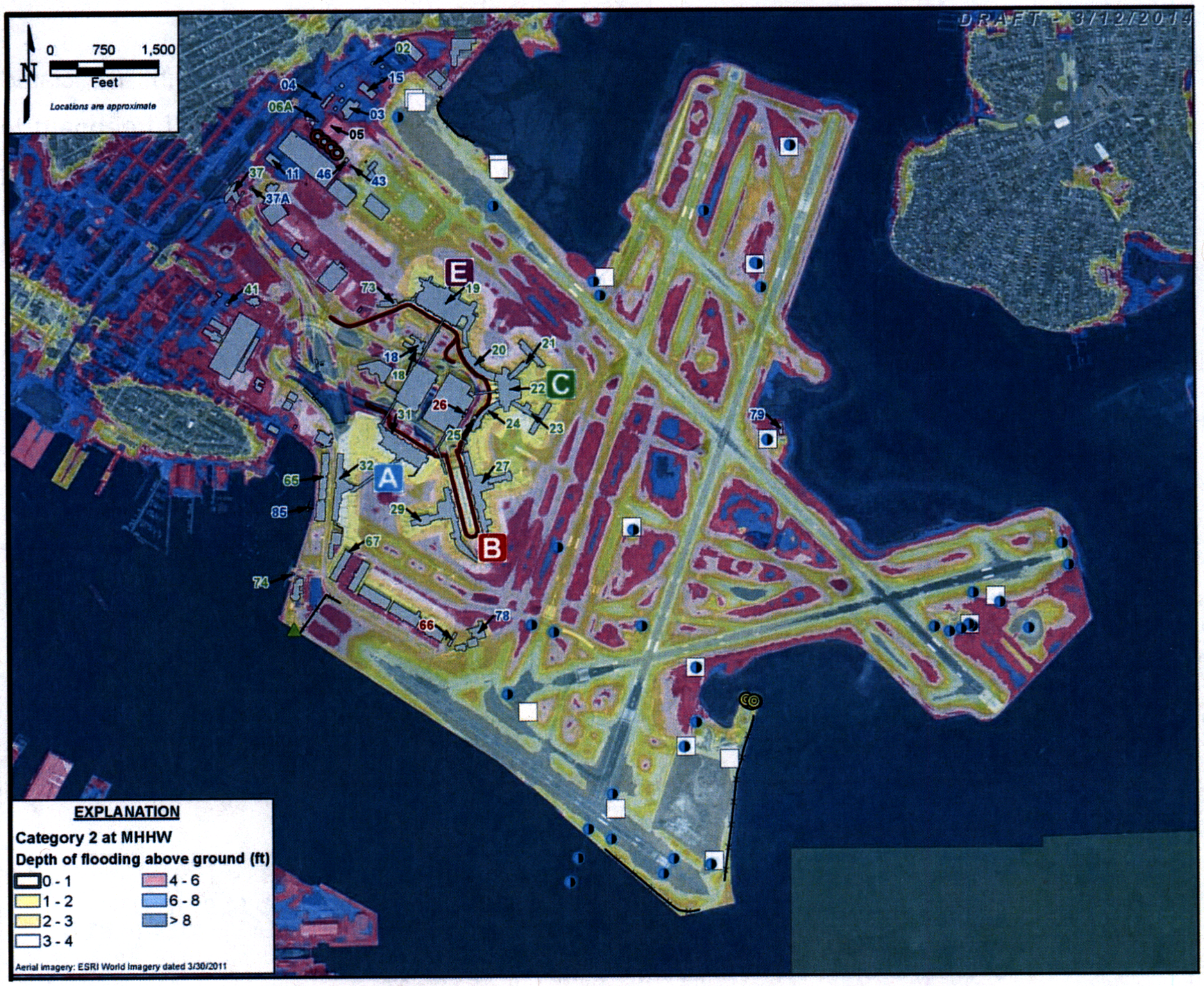


Figure 2 - Results of Category 2 Hurricane Hitting at MHHW – Logan Airport

An assessment of past weather events was conducted to determine the types of storms and tidal elevations that should be used for this assessment. Since 1858, there have been eight Category 2 hurricanes and two Category 3 hurricanes, which have made landfall within a 150 mile radius of Boston. Since two Category 2 hurricanes have occurred at MHW in the Boston Harbor area, and because of the extreme damage caused by Hurricane Sandy making landfall at Atlantic City as a Category 1 hurricane at MHHW, the scenario of a Category 2 or 3 hurricane making landfall at MHHW in Boston was selected as the worst-possible hurricane landfall scenario. It was deemed appropriate to consider the MHHW tidal elevation in the SLOSH simulations for determining the design flood elevation (DFE) for Logan Airport and the maritime facilities in South Boston.

For existing buildings, the DFE will be defined by the maximum storm surge height associated with a Category 2 Hurricane at MHHW (as modeled by SLOSH) plus one foot of freeboard to account for additional wave dynamics. This translates to an elevation of 17.75 ft for Logan and 17.25 ft for the maritime facilities in South Boston (see Figures 3 and 4).

For new construction, the maximum storm surge from a Category 3 hurricane hitting at MHHW will be used, which translates to a DFE of 21 ft for Logan Airport and 20.5 ft for the maritime facilities in South Boston (Figures 3 and 4). Due to the relatively low probability of a Category 3 hurricane occurring at MHHW, no additional freeboard will be used for new construction.

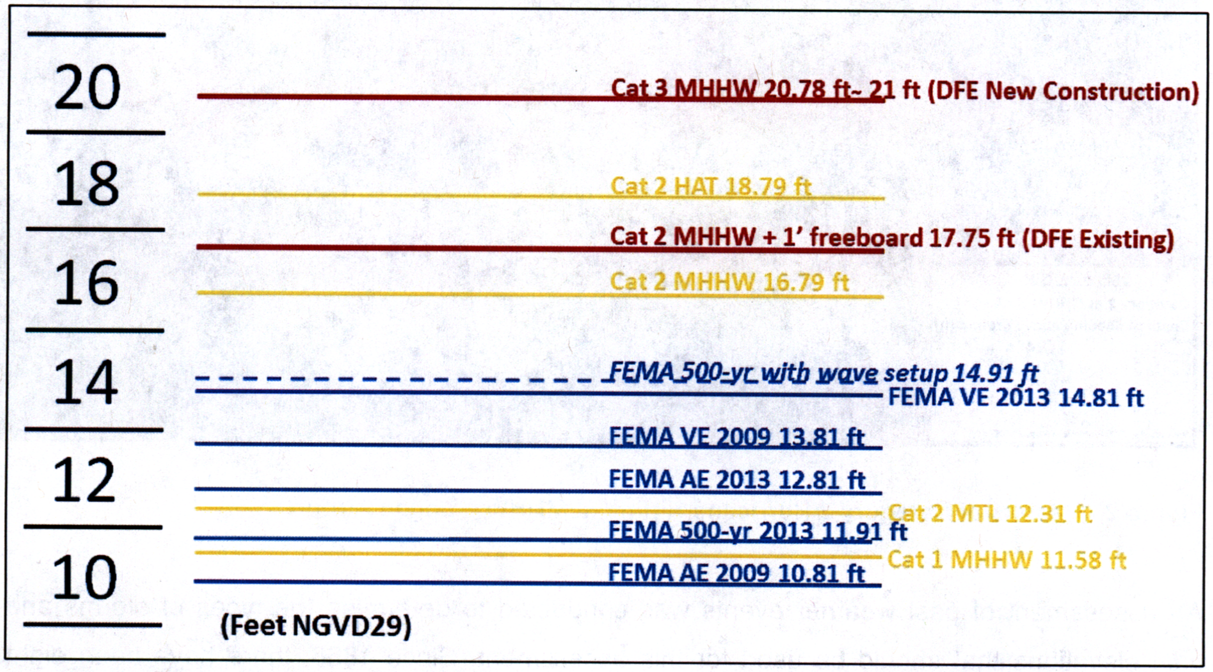


Figure 3 - Different Surge Elevations (in NGVD29 Datum) Considered in Determining DFEs at Logan Airport

Notes: *1. Hurricane elevations are based on maximum surge elevation for all critical facilities across Logan for present day. 2. Elevations are based on datum NGVD29 and lines showing elevations are approximately to scale. 3. For retrofitting existing infrastructure in Logan, Design Flood Elevation (DFE) is the maximum surge elevation from a worst-possible Category 2 hurricane at MHHW + 1 ft freeboard, rounded down to 17.75 ft NGVD29. For new construction in Logan, DFE is the maximum surge elevation from a worst-possible Category 3 hurricane at MHHW.*

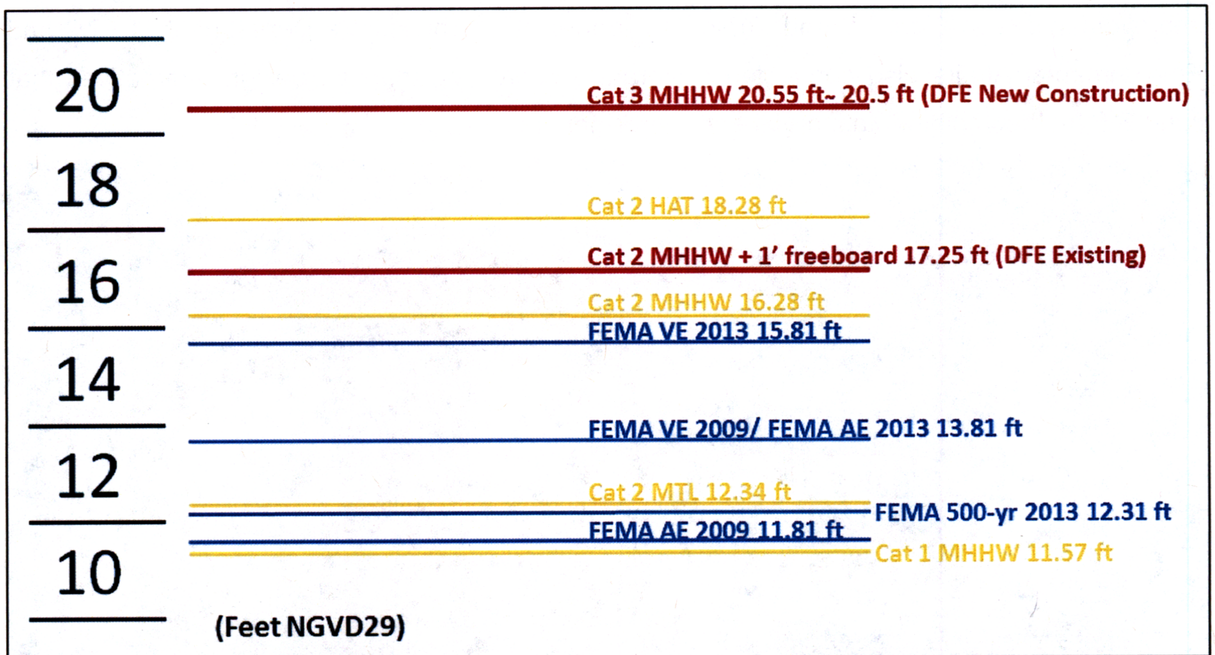


Figure 4 - Different Surge Elevations (in NGVD29 Datum) Considered in Determining DFEs at Maritime Facilities in South Boston

Notes: *1. Hurricane elevations are based on maximum surge elevation for all critical facilities across maritime facilities in South Boston. 2. Elevations are based on datum NGVD29 and lines showing elevations are to scale approximately. 3. For retrofitting existing infrastructure at maritime facilities in South Boston, Design Flood Elevation (DFE) is the maximum surge elevation from a worst-possible Category 2 hurricane at MHHW + 1 ft freeboard, rounded down to 17.25 ft NGVD29. For new construction at maritime facilities in South Boston, DFE is the maximum surge elevation from a worst-possible Category 3 hurricane at MHHW, rounded down to 20.5 ft NGVD29.*

Sea level is projected to rise in the Boston region in the range between 0.81 ft (NOAA "Highest" scenario) and 0.53 ft (NOAA "Intermediate-High" scenario) according to the 2012 report on "Global Sea Level Rise Scenarios for the United States National Climate Assessment." This elevation is accommodated within the proposed DFEs; therefore, no additional adjustments are included for sea level rise in the DFEs.

Vulnerability Assessment

Detailed facility assessments were developed for each critical asset identified at Logan Airport and the maritime facilities in South Boston. The assessments included information as to the use and construction of the building, the anticipated flood levels under the various scenarios, recommended floodproofing measures and order-of-magnitude cost estimates for those

improvements (see Figure 5 and Table 1). Northeastern University's Department of Civil and Environmental Affairs also conducted a literature search of adaptive design alternatives that could inform the implementation of these recommendations.

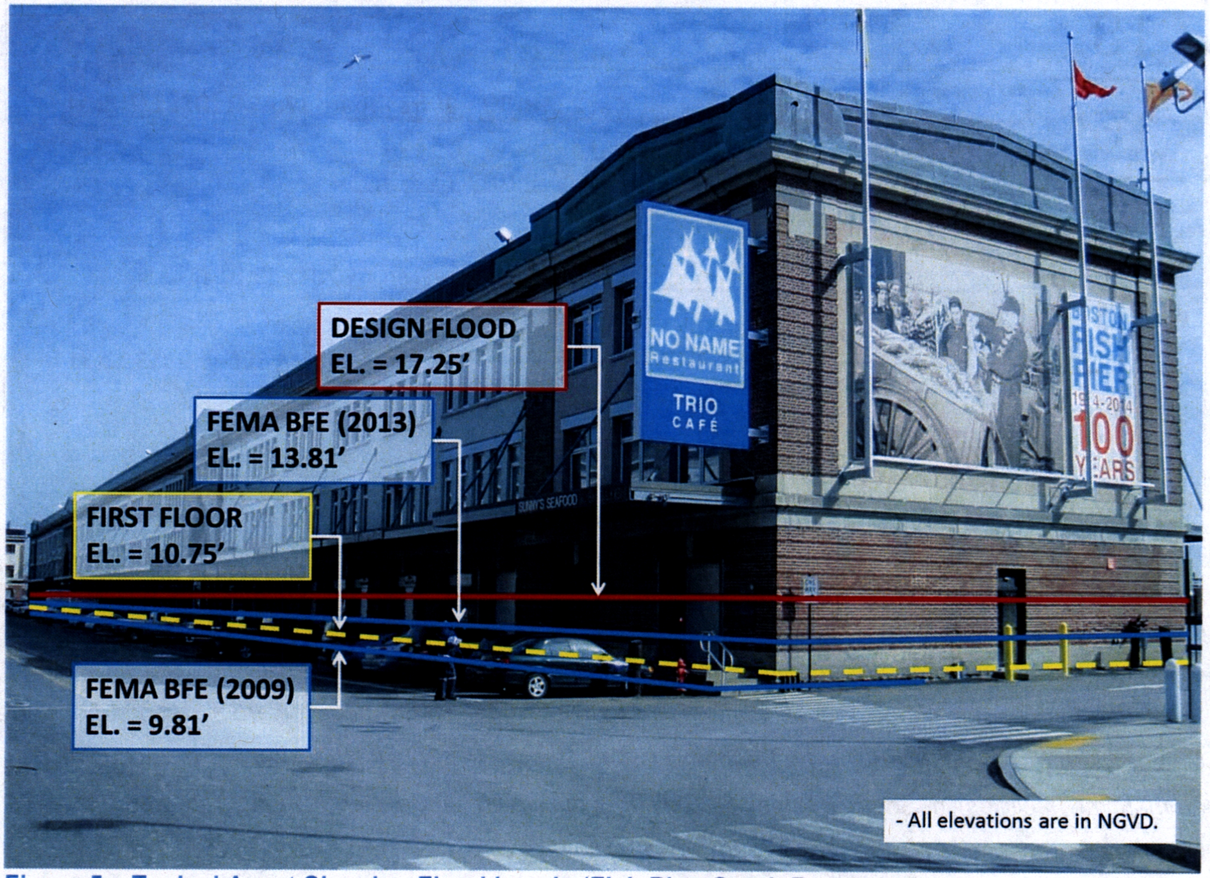


Figure 5 – Typical Asset Showing Flood Levels (Fish Pier, South Boston)

Notes: 1. Elevations are based on datum NGVD29 and lines showing elevations are approximately to scale. 2. For retrofitting existing infrastructure in maritime facilities in South Boston Maritime, the Design Flood Elevation (DFE) is the maximum surge elevation from a worst-possible Category 2 hurricane at MHHW + 1 ft freeboard, rounded down to 17.25 ft NGVD29. 3. "FEMA BFE" refers to the historic Base Flood Elevations (0.1% annual chance) as reported on the current (2009) and the proposed revised (2013) Flood Insurance Rate Maps published by the Federal Emergency Management Agency under the National Flood Insurance Program.

Resiliency Recommendations

Recommendations were prioritized using a risk-based methodology that took into account the probability and consequence of flooding for each asset. Those assets with the highest probability and consequence of flooding were considered the highest priority for resiliency

investment. Probability was assessed by comparing flooding results at each location across a number of modeled storm scenarios (based on SLOSH model results). Consequence of failure was qualitatively assessed for each asset, considering its Structural Category (as outlined in ASCE/SEI 24-05: *Standard for Flood Resistant Design and Construction*) and Criticality (as defined in collaboration with Massport stakeholders). Finally, assets with a common probability and consequence of flooding were further ranked based on depth of flooding. The methodology yielded an overall framework to help Massport decision makers prioritize resiliency implementation across facilities and infrastructure systems. A summary of the prioritized assets and estimated capital costs for flood resiliency improvements are shown in Table 1.

It is important to note that, while the risk-based prioritization provides a framework for planning resiliency-focused capital improvements, it is not the sole basis for decision making. Individual investment decisions are based on the merits of the prospective project, taking into account Massport's broader investment strategies, the impact to overall revenue generation, and business continuity concerns. The relative economic importance of Massport facilities will likely be factored into the over prioritization when deciding how or when to allocate resiliency resources. Decision making should also be flexible enough to allow for opportunistic resiliency investments to be considered as they arise.

Table 1 – Recommended Prioritization for Capital Planning

Facility	Asset Name(s)	Critical Functions	Estimated Capital Costs
TIER 1 – HIGHER PROBABILITY			
HIGHER CONSEQUENCE			
Conley	Site Switch House	Electrical	$ 140,000
Conley	Wharf Switch Houses No. 1-3, Marine Operations Center	Electrical	$ 254,000
Logan	Fire-Rescue II (L79)	Public Safety	$ 15,000
Logan	Marine Fire-Rescure (L85)	Public Safety	$ 345,000
Logan	Wood Island Substation (L02)*	Electrical	$ 359,000
Logan	Porter Street Substation (L41)*	Electrical	$ 474,000
		SUBTOTAL	**$ 1,587,000**
INTERMEDIATE CONSEQUENCE			
Fish Pier	Fish Pier Berths, East Building, West Building, Electrical	Multiple	$ 790,000
Conley	Berths 11-12	Access	$ 500,000
Conley	Rubber Tire Gantry Cranes	Cargo	$ 190,000
Conley	Vessel Cranes 1-6	Cargo	$ 1,650,000
		SUBTOTAL	**$ 3,130,000**
LOWER CONSEQUENCE			
Conley	Interchange Facility	Cargo	$ -
Conley	Reefer Building and Yard	Electrical	$ 200,000
		SUBTOTAL	**$ 200,000**
		TIER 1 TOTAL	**$ 4,917,000**
TIER 2 – INTERMEDIATE PROBABILITY			
INTERMEDIATE CONSEQUENCE			
Conley	Fuel Island and USTs	Fuel	$ 70,000
			$ 70,000
LOWER CONSEQUENCE			
Black Falcon	Gangway / FMT	Passenger	$ 150,000
		SUBTOTAL	**$ 150,000**
		TIER 2 TOTAL	**$ 220,000**
TIER 3 – LOWER PROBABILITY			
HIGHER CONSEQUENCE			
Logan	ATC Tower, Substation, and Generator (L26)	Aviation	$ 61,000
Logan	MPA Administration Building / Boutwell (L25)	Administration	$ 882,000
Logan	Bird Island Flats Substation (L67)	Electrical	$ 187,000
Logan	Airfield Lighting Vault (L66)	Aviation	$ 296,000
Logan	Harborside Substation (L32)	Electrical	$ 74,000
Conley	Gate Switch House	Electrical	$ 340,000
Logan	Logan Office Center (L65)	Administration	$ 749,000
Logan	MPA Pumping Station, Electrical Building, Generator (L06A/B)	Water	$ 854,000
Logan	State Police & TSA Building (L11)	Public Safety	$ 822,000
Logan	Central Heating Plant / Facilities I (L18)	Utilities	$ 895,000
Logan	Boston EMS Station (L43)	Public Safety	$ -
Logan	Fire-Rescue I (L78)	Public Safety	$ 426,000
		SUBTOTAL	**$ 5,686,000**
INTERMEDIATE CONSEQUENCE			
Logan	Facilities II	Maintenance	$ 278,000
Conley	Administration Building, Substation	Administration	$ 235,000
Logan	BOSFuel Operations Building, Tank Farm, Fuel Island (L46)	Fuel	$ 503,000
Conley	Administration Building Generator	Electrical	$ 300,000
Black Falcon	Main Terminal Building	Passenger	$ 252,000

Facility	Asset Name(s)	Critical Functions	Estimated Capital Costs
TIER 3 – LOWER PROBABILITY			
INTERMEDIATE CONSEQUENCE			
Logan	Terminal E and West Baggage Screening Room (L19, L73)	Passenger	$ 1,356,000
Logan	Terminal C (L20-L24)	Passenger	$ 3,695,000
Logan	Terminal A (L31, L32)	Passenger	$ 827,000
Logan	Terminal B (L27, L29)	Passenger	$ 3,067,000
Logan	West Outfall (Bar Screen Building)	Drainage	$ 13,302,000
Conley	Operations Building	Maintenance	$ 200,000
Conley	Massport Police Pro Shop Building	Public Safety	$ 78,000
Conley	Massport Police Main Gate Guard House	Public Safety	$ 5,000
Logan	Tunnel T18C (Tunnel Intersection to Terminal C)	Utilities	$ 200,000
Logan	Facilities III (L04)	Maintenance	$ 792,000
Logan	North Gate (L44)	Public Safety	$ 8,000
Logan	South Gate	Public Safety	$ 7,000
		SUBTOTAL	**$ 25,105,000**
LOWER CONSEQUENCE			
Logan	Fire Training Facility (Hazardous Waste)	Environmental	$ -
Logan	Large Vehicle Storage Building (L15)	Maintenance	$ 302,000
Logan	Water Shuttle Pier (L74)	Access	$ -
Conley	Reefer Substation	Electrical	$ 800,000
Logan	Tunnel T18E (CHP to Terminal E)	Utilities	$ 194,000
Logan	Tunnel T31B (Terminal A to Terminal B)	Utilities	$ 154,000
Logan	Tunnel T18A (Intersection to Terminal A)	Utilities	$ 170,000
Haul Road	Haul Road Sump Pump	Drainage	$ -
Logan	Tunnel T18B (CHP to Intersection)	Utilities	$ 200,000
Logan	Tunnel T18D (Old CHP Tunnel - Partly Abandoned)	Utilities	$ 50,000
Logan	Tunnel T31A (Termina A Main to Satellite)	Utilities	$ 132,000
		SUBTOTAL	**$ 2,002,000**
		TIER 3 TOTAL	**$ 32,793,000**
		TIERS 1-3 TOTAL	$ 37,930,000

*Due to the asset's strategic nature and its high depth of flooding under Category 2 hurricane at MHHW, high priority is warranted, including hydraulic modeling to investigate flood risk from rainfall combined with less severe storm scenarios.

Seven other recommendations were developed to guide the implementation of Massport's climate resiliency plans over the coming years:

1. Mobilize $50 million for flood resiliency investments in critical infrastructure over the next 10 years, as identified in the prioritized recommendations.
2. Strengthen design standards and guidelines for enhanced flood resiliency.
3. Develop and update operational plans related to emergency management and flood protective actions in coordination with key stakeholders.
4. Raise awareness among Massport employees, tenants, and lessees of hurricane wind and flood risks as well as ongoing resiliency efforts.

5. Engage with external partners to cooperate on identified resiliency issues of common interest.
6. Expand and increase the scope of studies to investigate climate and natural hazard risks and resiliency measures.
7. Monitor, report, and periodically update the Resiliency Plan.

The proposed Resiliency Plan will help Massport address the most significant risks to its infrastructure over the coming decades due to sea level rise and extreme flooding events, as well as put in place programs to address broader climate risks. With the information produced for this report, Massport can weigh the costs and benefits of proposed capital investments, emergency planning, and disaster response and recovery measures and implement programs and projects that fit its needs.

2. INTRODUCTION

2.1 Scope and Purpose

In 2013, the Massachusetts Port Authority (Massport) retained Kleinfelder, Inc. to perform a *Disaster and Infrastructure Resiliency Planning Study (DIRP)*, which focused on the risks associated with extreme weather events and climate change. It included a hazards analysis, a vulnerability assessment, and resiliency recommendations for both near-term and longer-term capital improvements. This project was performed under Massport Contract No. A267-D9/GG-9405.

The DIRP report identified numerous Logan Airport and maritime facilities in South Boston that are vulnerable to the effects of coastal flooding and storm surge. A prioritized list of recommendations was made for capital improvement projects to mitigate the effects of flooding with the goal of reducing potential negative impacts to health and safety, business operations and property damage.

This report brings together information from all phases of the project and presents a Resiliency Plan for Massport to protect its critical infrastructure from climate-related disasters that could reasonably occur in the next 20 years. Recommendations presented are intended to be actionable, measurable, scalable, and financially feasible and they address operational and emergency response issues as well as infrastructure.

2.2 Overview

A recent study concluded that, due to its vulnerabilities to climate change and sea level rise, Boston will incur higher costs from coastal flooding than all but seven of the largest 136 coastal cities in the world by 2050.[1] These long-term economic impacts can largely be avoided if adequate investments are made to increase disaster resiliency, starting with regionally critical infrastructure.

The time for Boston infrastructure owners to begin planning and implementing resiliency investments is now, and Massport has taken an important first step by undertaking this *Disaster*

---

[1] *Stephane Hallegatte, Colin Green, Robert J. Nicholls & Jan Corfee-Morlot (2013). Future flood losses in major coastal cities. Nature Climate Change 3, 802–806*

and Infrastructure Resiliency Planning Study. Recent multi-billion dollar climate disasters, such as Hurricane Sandy, have provided insights into how extreme climatic events can impact critical transportation infrastructure, including airports and ports, and degrade a region's capabilities to provide and support health and safety, commerce, and mobility. Massport recognized these risks and commissioned this Disaster and Infrastructure Resiliency Planning Study (DIRP) to begin addressing them.

Understanding and managing the risks of extreme climatic events, like Hurricane Sandy, is especially relevant for Massport, as it is a critical infrastructure owner and engine of economic activity for Metro Boston and the New England region. Some of Massport's most critical infrastructure, including Logan Airport and the maritime facilities in South Boston, are located in relatively low-lying coastal areas. Such areas tend to have high exposures to extreme storm surge, wind, and precipitation from hurricanes and nor'easters.

In the aftermath of disasters, airports, like Logan Airport, play an important role in supporting aviation activities for regional disaster response, including airborne search and rescue, medical evacuation, movement of emergency medical supplies and emergency personnel, fire-fighting and law enforcement, damage assessment surveys, and media and VIP transport.[2]

Furthermore, Massport is a self-financing agency, relying on the revenue it generates to pay its capital and operational expenses. Climatic disasters, if not adequately planned for, could deal a double-blow to Massport's financial sustainability by simultaneously reducing revenues and increasing capital and operational costs.

Massport has already experienced the economic impacts of extreme weather events. For example, Hurricane Sandy cost Massport approximately $3.5 million in infrastructure damages and business losses, even though it made landfall over 300 miles away. A recent study found that had Sandy's storm surge arrived several hours earlier in Boston, at high tide rather than low, the impacts to Massport facilities and Metro Boston would have been far worse.[3]

---

[2] *Jean B. Perkins (2013). Roles of Airports in Regional Disasters: Lessons on Disaster Response, Short-Term Disaster Recovery, and Long-Term Economic Recovery for the San Francisco Bay Area. Association of Bay Area Governments.*

[3] *Ellen Douglas, Paul Kirshen, Vivien Li, Chris Watson, and Julie Wormser (2013). Preparing for the Rising Tide Report. The Boston Harbor Association.*

Major winter storms, including nor'easters, regularly disrupt Massport's maritime and air transportation operations, resulting in short-term revenue losses as well as capital investment costs for infrastructure and equipment. The regularity of major winter storms has made it easier to plan for these costs and to rationalize investments that reduce the risk these storms pose.

However, Massport has not experienced the full brunt of a powerful hurricane hitting Boston directly at high tide. The economic, social, and environmental impacts of such a disaster, described in this report and others, would be much more extensive than any extreme climate events Massport has experienced in the past.

2.3 Project Goals and Objectives

Massport initiated the DIRP project to improve its understanding and management of the risks posed by a changing and more extreme climate. As indicated in the project's name, DIRP's primary focus is on infrastructure risk and resiliency. Operational issues are considered within the scope of DIRP, insomuch as they relate to emergency planning, disaster response, and disaster recovery for infrastructure. Other projects are focusing on broader operational resiliency at Massport.

DIRP was divided into multiple interdependent phases, with the following objectives:

- Analyzing the historic occurrence of different climate hazards as well as their current and future trends under climate change;
- Establishing the criticality and existing conditions of Massport's infrastructure systems and assets;
- Assessing the vulnerability and risk of Massport's critical infrastructure in light of current and future climate hazards;
- Developing infrastructure resiliency recommendations to reduce disaster risks, both for the near and longer term; and,
- Developing a Floodproofing Design Guide to provide an overview of the principal planning and design considerations for improving the performance of critical Massport facilities during, and in the aftermath of, flooding events.

2.4 What to Keep In Mind When Reading and Interpreting This Report

The science of climate change and translating climate risks into design criteria are new and evolving practices, involving many uncertainties. Therefore, the projections made in this report only reflect the professional judgment of the Project Team applying a standard of care consistent with the practice of other professionals undertaking smiliar work. For these reasons, the recommendations and projections made within this report provide guidelines for investment decisions based on the knowledge to date. The flood level predictions made in this report are based on some of the most recent developments in the science of climate change but are not guaranteed predictions of future events. It is recommended that these results be updated over time as science, data and modeling techniques advance.

The scope of this contract did not include a full review of building and facility drawings, material testing, survey or structural analysis of the building's ability to withstand the projected hydrostatic forces due to flooding. The findings include certain assumptions based on reasonable engineering judgment as to the ability of buildings and facilities to resist the projected hydrostatic forces due to flooding. These assumptions will require additional verification and customization during the deign phase of individual projects.

3. CLIMATE ANALYSIS – PAST EVENTS AND FUTURE TRENDS

The increase in extreme weather events in recent years has led to costly and disruptive disasters, particularly with respect to infrastructure. Recent local events such as Winter Storm Nemo and Hurricane Sandy have highlighted some of those vulnerabilities within Massport's infrastructure. This report recommends likely climate scenarios that Massport should consider when planning for resiliency.

This study focuses on Logan Airport and the maritime facilities in South Boston. Three planning horizons were used: immediate (a storm making landfall tomorrow), short term (1-5 years out) and longer term (20 years out to the year 2033). While the analysis of impacts and subsequent DFE focused on storm surge and sea level rise (SLR), climate indicators for precipitation, temperature and wind have were also assessed and included here for potential use in future studies.

The following recommended climate scenarios were developed drawing upon historic trends, projected changes from downscaled data, and lessons learned from other storm events such as Hurricane Sandy. The recommended scenarios are as follows:

- **Sea Level Rise**: Assume 0.53 feet (6.4 inches) of sea level rise in Boston Harbor by 2033.
- **Storm Surge:** Use SLOSH Model results simulating storm surge heights and resulting inundation at Massport facilities under different hurricane scenarios. Compare inundation results against current and revised Federal Emergency Management Agency (FEMA) flood insurance rate maps.
- **Precipitation:** Assume more frequent, more extreme precipitation events; higher average annual precipitation, mostly from increases in winter and spring; less snow (due to projected temperature increase).
- **Temperature:** Assume more frequent, more extreme high temperature events (days greater than 90°F and 100°F) and fewer frequent days below freezing; higher average annual temperature, mostly from increases in winter and summer. Monitor extreme temperature during summer months and potential impacts to pavement design, cooling loads, increased energy usage associated with such.

- **Wind:** Assume wind speeds and wind gust speeds to remain consistent with long-term historical averages (1945-2012) since the climate science is not advanced enough at this stage to make reliable predictions otherwise.

3.1 Sea Level Rise

Recommendation: Assume 0.53 feet (6.4 inches) of sea level rise in Boston Harbor by 2033.

Over the past century, sea levels have been rising as a result of climate change. Oceans have warmed, causing their volumes to expand, and glaciers and land-based ice have melted, contributing additional fresh water to the oceans' volumes. Global sea level rise (SLR) and relative SLR in Boston have been occurring at average rates of 0.07 in/yr (NOAA 2012), and 0.11 in/yr (NOAA 2013), respectively. Relative SLR in Boston has been higher than global SLR because the local landmass in Boston has been sinking at an estimated rate of 0.04 in/yr, the result of long-term geological processes.

Sea level rise is expected to continue, and even accelerate in the future, due to climate change. To provide Massport with reasonable estimates of future sea levels at its facility locations, relative SLR in Boston Harbor has been projected up to the year 2033 from the baseline year of 2013 (the year DIRP was initiated). The projections are based on the "Intermediate-High" scenario for global SLR as shown in the NOAA Technical Report *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (December, 2012), as well as the estimated rate of local land subsidence in Boston (0.04 in/yr).

Estimates of total relative SLR in Boston Harbor are listed in Table 2, including for 2033, and in increments of 10 years from 2020 through 2100. As indicated in the table (red text), sea level in Boston Harbor is projected to rise a total of 0.53 ft (6.4 in) by 2033, with 0.47 ft (5.6 in) from global SLR and local land subsidence contributing an additional 0.06 ft (0.72 in).

The NOAA (2012) "intermediate-high" scenario for global SLR is based on an average of the high end of semi-empirical global SLR projections (Grinsted et al. 2009, Jevrejeva et al. 2010, Vermeer and Rahmstorf 2009, Horton et al. 2008). The difference between this scenario and the "highest" scenario is in the rate and magnitude of ice sheet loss from Greenland and West Antarctica. The later is based on a calculation of maximum possible glacier and ice sheet loss by 2100.

Table 2 – "Intermediate-High" Scenario Projections for Relative SLR in Boston (2013-2100)

Scenarios	2020	2030	2033	2040	2050	2060	2070	2080	2090	2100
Total Relative SLR (ft)[1]	0.16	0.44	0.53	0.77	1.16	1.61	2.12	2.68	3.30	3.98
Global SLR – "Intermediate-High" (ft)[2]	0.14	0.38	0.47	0.68	1.04	1.46	1.93	2.46	3.05	3.69
Land subsidence (ft)[3]	0.02	0.06	0.06	0.09	0.12	0.15	0.19	0.22	0.25	0.29

[1] Total relative SLR is calculated here as the sum of global SLR and local land subsidence. The base year is 2013.

[2] "Intermediate-high" scenario of global SLR is based on the 2012 NOAA Technical Report on Global Sea Level Rise Scenarios for the United States National Climate Assessment, December 2012.

[3] Land subsidence in Boston is estimated to be 0.04 in/yr for the purposes of this assessment.

3.2 Storm Surge

Recommendation: Use SLOSH Model to simulate storm surge heights and resulting inundation at Massport facilities under different hurricane scenarios. Compare inundation results against current and revised Federal Emergency Management Agency (FEMA) flood insurance rate maps.

Storm surge is a temporary rise of sea level caused by the passing of a low pressure weather system such as a hurricane or nor'easter. The low pressure around the eye of a storm causes local water levels to rise, and high winds push water in front of the storm, creating waves and a rise of local water levels where water is pushed against the coast. The magnitude, or height, of a given storm surge depends on the associated storm's intensity (minimum pressure and wind speed) and direction of movement as well as the shape and depth of impacted coastal waters. In addition to surge height, other factors such as storm size, surge duration, elevation of adjacent land, and the point in the tidal cycle at which the surge reaches its peak all contribute to the extent of coastal flooding and damage that a given event will cause.

To assess the exposure of Massport properties in Boston to storm surge inundation caused by hurricanes and nor'easters, three different methods of analysis were used. First, historical data were analyzed to determine the recurrence and magnitude of past storm surges and associated storm events. Second, the latest scientific literature assessing historical trends and future climate change projections was reviewed and summarized. Finally, based on the historical

analysis and scientific literature, storm surge modeling for specific storm types and intensities was conducted using the hydrodynamic Sea, Lake, and Overland Surge from Hurricanes (SLOSH) Model developed by the National Weather Service. SLOSH is a computer model used to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. The resulting inundation maps[4] were compared with current and revised FEMA flood insurance rate maps.

Historic water elevation observations in Boston Harbor[5] were analyzed using methods described in Kirshen et al. (2008) to estimate the recurrence of various extreme storm surge heights. Storm surge heights were estimated by calculating the difference between the observed water level elevation and the water level elevation predicted by the NOAA tide model, accounting for local subsidence and historical sea level rise trends. Maximum annual surge heights were then identified and statistically analyzed to calculate the storm surge heights for various recurrence intervals (e.g., 10, 50, 100, 100 years). The results are shown in Figure 6.

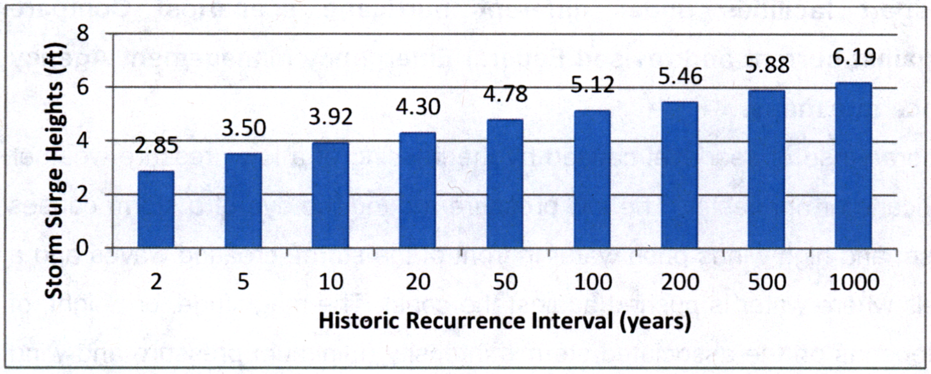


Figure 6 – Historic Recurrence of Storm Surge Heights in Boston Harbor (1921-2012)

3.2.1 Hurricanes

Historical analysis of hurricane data shows that since 1858 Boston has been impacted by an estimated 23 hurricanes of varying intensities. The most intense hurricanes to pass within 150 miles of Boston were two Category 3 hurricanes (defined by 1-minute sustained wind speeds of 111-129 mph), eight Category 2 hurricanes (96-110 mph), and 13 Category 1 hurricanes (74-95

[4] *Inundation analysis is conducted using geographic information systems to estimate flood depths at different locations by overlaying and comparing storm surge elevations estimated by SLOSH, and land elevations estimated by interpreting LiDAR data.*

[5] *NOAA Station ID 8443970*

mph). Although their probability of occurring in any given year is low (1% for a Category 3, and 5% for a Category 2), it is reasonable to expect, based on historical recurrence and years since last occurrence, that Massport will be impacted by two or three hurricanes of such intensity by 2033. In addition, there is moderate certainty, based on scientific literature, that average hurricane intensity will increase in the future as a result of climate change, the result being more frequent stronger storms as compared to fewer weaker ones (Emanuel 2013, IPCC 2012, Knutson et al. 2013, Moser et al. 2012). As described in Section 4 (*Methodology for Selecting Design Storm Elevations*), storm surge inundation scenarios for hurricanes of different intensities striking at different tidal elevations were modeled using SLOSH to assess potential flood risk as Massport facilities and develop appropriate solutions.

3.2.2 Nor'easters

Cold season extratropical storms, known as nor'easters, are large closed (i.e. circular or oval-shaped), low pressure systems that form in the Atlantic and move up the coast, typically in winter months. Historical analysis conducted for this study shows that nor'easters have been responsible for 72% of the highest annual storm surges in Boston Harbor since 1952, including the highest storm surge in that period (6.19 feet on February 26, 2010). There is some evidence that the frequency and intensity of these storms have increased in coastal New England since 1950 (Vose et al, 2013). However, there is limited certainty about whether these events will become more or less frequent and intense in the future due to climate change. Given that nor'easters occur frequently and cause such a large proportion of maximum annual storm surges, it is reasonable to assume that Boston will be impacted by nor'easter-driven storm surge over the next 20 years.

3.3 Precipitation

Recommendation: Assume more frequent, more extreme precipitation events; higher average annual precipitation, mostly from increases in winter and spring; less snow (due to projected temperature increase). Incorporate new values based on climate projections for 24 and 48 hour design storms (10, 25, 100 year) in stormwater systems studies and designs.

Analysis of historical precipitation data from Logan Airport and downscaled climate projections produced for this project show that average conditions in Boston have become wetter and will continue to do so up to the 2033s[6].

Future projections of precipitation and temperature are based on simulations from multiple global climate models under a higher and lower future emissions scenario that have been "downscaled" to the Boston Logan Airport weather station. This means that global climate model outputs, which are usually provided in geographic grid cells ranging in size from 50 to 250 square miles, are statistically calibrated to a specific weather station – in this case, Boston Logan Airport – based on that station's historical data. Converting global climate model outputs from a large spatial scale to a smaller spatial scale is called "downscaling".

Since 1936, statistically significant increases have been documented in the amount of precipitation falling on the wettest day of the year. Over the last 50 years (from 1961 to 2010), there have also been statistically significant increases in annual and summer precipitation. Cumulative annual precipitation at Logan Airport averaged 43.6 in/yr for the historical period 1971-2000. This amount is projected to increase to 45.4 in/yr by the 2033s. Most of this projected increase is in winter and spring. As temperatures increase, the amount of future snowfall is projected to decrease, from a historical average of 4.8 in/yr (liquid water equivalent)[7] to 3.7 in/yr by the 2033s.

Increasing frequency of heavy precipitation events is projected for Logan Airport. The number of days per year with more than 2 inches of precipitation in 24 hours is projected to increase from 2 days to between 2.2 and 2.6 days in the 2033s. Long duration storms are also expected to become more intense, with precipitation falling on the five consecutive wettest days of the year increasing from the historical average of 5.4 inches to 6.4 inches.

---

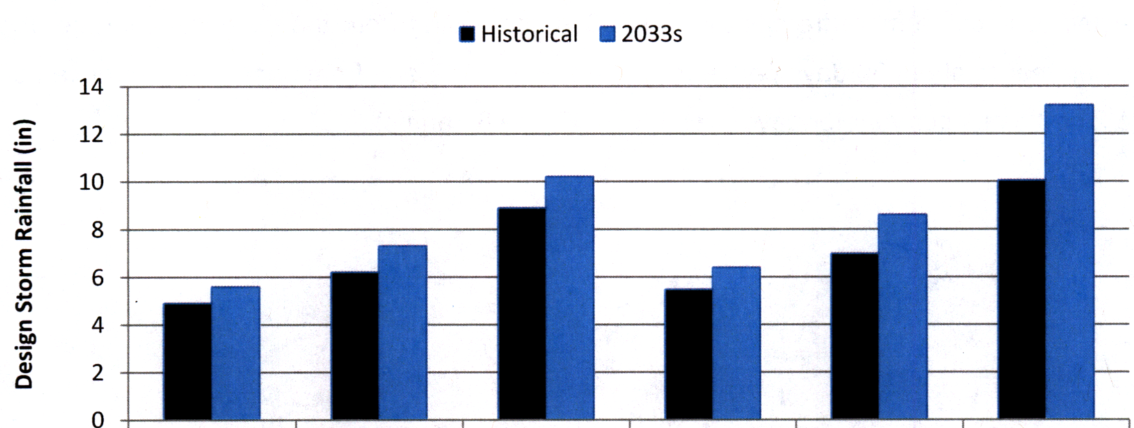
[6] *The term "2033s" is used in reference to averages of the projections for the 30-year climatological period around the year 2033 (2018-2047). Averaging has been applied, rather than simply selecting data from the year 2033, in order to incorporate a representative range of naturally-occurring year-to-year fluctuations, or weather, that are mimicked by the models, including accounting for the El Nino effect.*

[7] *Analysis of future snowfall is expressed at liquid water equivalent. Climate projections generally refer to precipitation, rather than rain or snow, since whether precipitation falls in liquid or solid form often depends on the vertical profile of temperature (air temperature at different altitudes), which is typically not well resolved by either weather station observations or climate models. It is possible to approximate projected changes in the proportion of snow vs. rain by making an assumption regarding the conditions under which snow may fall. Here, we assume that precipitation falls as snow if maximum daytime air temperature is below 2°C.*

3.3.1 Design Storms

Design storms are used to assess level of service requirements, determine carrying capacities of pipes and locations of overflows in existing drainage infrastructure, and serve as the basis for designing new drainage infrastructure. As heavy precipitation becomes more frequent, design storms based on historic data are likely to under-predict future precipitation events. For this reason, new construction projects designed to alleviate flooding and upgrades to existing stormwater infrastructure to mitigate flooding impacts need to be evaluated in terms of future rainfall trends.

A collaborative effort among the City of Cambridge and Boston Water and Sewer Commission recently resulted in the calculation of design storm values that take climate change into consideration for the upcoming decades. Projected rainfall depths associated with 24-hr and 48-hr duration design storms with recurrence intervals of 10-, 25- and 100-years were estimated for mid-century (2030s) and later-century (2070s) time frames (Figure 7). For these design storm estimates, the entities reached consensus on using the same design values, thus building regional consistency and ensuring compatibility between systems that intersect across municipal boundaries. It is recommended that the same design storm estimates by 2030s are used for Massport to be in agreement with other regional studies.



	10 yr–24 hr	25 yr–24 hr	100 yr–24 hr	10 yr–48 hr	25 yr–48 hr	100 yr–48 hr
Historical	4.91	6.21	8.88	5.48	6.97	10.04
2033s	5.6	7.3	10.2	6.4	8.6	13.2

Figure 7 – Historical and Projected 24hr and 48hr Design Storms in 2033s (10, 25, and 100yr)

Note: Based on data developed for Boston Water and Sewer Commission and the City of Cambridge.

3.4 Temperature

Recommendation: Assume more frequent, more extreme high temperature events (days greater than 90°F and 100°F) and fewer days below freezing; higher average annual temperature, mostly from increases in winter and summer.

Analysis of historical temperature data from Logan Airport and downscaled climate projections produced for this project show that average conditions in Boston have become warmer and will continue to do so up to the 2033s. Average annual temperature at Logan Airport is projected to increase from about 51°F in the historical period (1971-2000) to about 55°F by the 2033s. Winter temperatures, which historically average 31°F, and summer temperatures, which average 71°F, are also expected to increase, to about 35°F and 76°F respectively.

Since 1936, average minimum temperatures throughout the year and in all seasons have been getting warmer, and days below freezing have been occurring less frequently.[8] Downscaled climate projections produced for this project indicate that the number of days per year with temperatures below freezing (32°F) will continue to decrease, from a historical average of 95 days (1971-2000) to 75 days by the 2033s (Figure 8a).

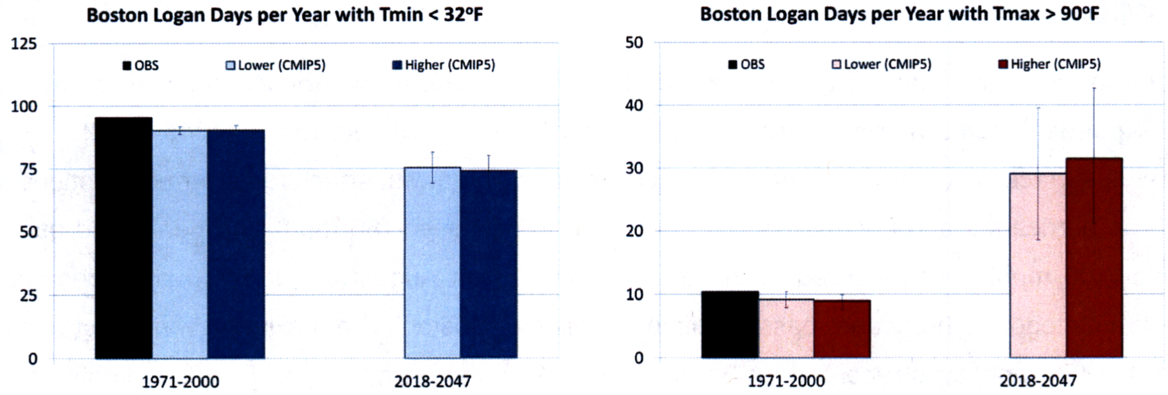
Over the past 50 years (1961-2010), average maximum temperatures throughout the year and in winter have been increasing.[9] Days with maximum temperatures over 90°F and 100°F are projected to become more frequent in the 2033s, increasing from the historical average of 10 days per year to about 30 days per year for days over 90°F, and from once every eight years or so to 2 or 3 times per year for days over 100°F (Figure 8b and c).[10]

[8] *These trends are statistically significant.*

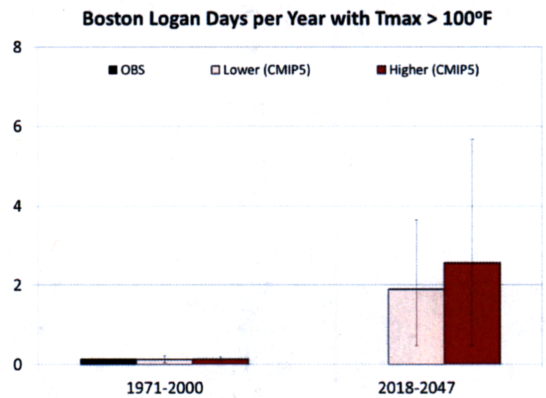
[9] *These trends are also statistically significant.*

[10] *The downscaled results from older climate models suggest that, by the 2033s, days above 100°F could occur only once every one or two years.*

(a) (b)



(c)



Historical (1971-2000) and projected future (2018-2047, "2033s") days per year with: (a) minimum temperature < 32°F, (b) maximum temperature > 90°F, and (c) maximum temperature > 100°F. Light red or blue temperature bars show projected changes under lower scenarios; dark red or blue temperature bars, under higher. Black bars are the observed data to date. CMIP5 are the newer generation of climate models. The ranges on each bar show the projections from all the different models in each group (9 CMIP5 models).

Figure 8 (a), (b), and (c) – Average Number of Days/Year with Extreme Temperature

The potential for runway asphalt failures occurring at Logan Airport in the future due to extreme temperatures was considered. During a 10-day heatwave in 2012, pavement failure occurred at Ronald Raegan Washington National Airport in Washington, DC. The asphalt binder used at Logan Airport has an operating temperature range of between -18°F and 147°F. There are no days at Logan Airport, either in the historical record or in climate projections, with temperatures beyond these thresholds. It appears that runways may be resilient to the expected temperature ranges that they will be exposed to, though temperatures on dark surfaces close the ground may be higher than the general ambient air temperature monitored at the airport and projected by climate models.

3.5 Wind

Recommendation: Assume extreme wind threshold exceedances and average wind and gust speeds to remain consistent with long-term historical observations (1945-2012). Extreme surface winds at Logan Airport are chiefly associated with structured storm circulations, such as hurricanes and nor'easters. The maximum wind speed (86 mph) and peak wind gust speed (100 mph) ever recorded at the airport occurred on August 31, 1954 when Hurricane Carol, a Category 2 hurricane, passed within 75 miles of Boston. The maximum wind gust ever recorded (98 mph) was recorded on February 9, 2013 during a nor'easter popularly known as Winter Storm Nemo.[11] Since the science of predicting changes in wind associated with climate change has yet to be fully developed, the historic record is being used to inform decisions here.

There are several important wind thresholds for Massport's infrastructure and operations. The historical frequencies of wind threshold exceedances are summarized in Table 3.

Table 3 – Historic Frequency of Wind Threshold Exceedances at Logan Airport

Indicator		Historic Frequency (days/year)
Wind Thresholds	Wind speed ≥ 40 mph (high wind) [1]	2.3
	Peak wind gust ≥ 78 mph (ATC Tower evacuation) [2]	0.2
	3-second gust ≥ 105 mph (basic wind speed from MA building code) [1, 3]	0.01

[1] Based on Wind Speed data from 1945-2012.
[2] Based on Peak Wind Gust data from 1950-1995.
[3] The frequency of 3-second gust speeds exceeding 105 mph is calculated based on Wind Speed conversions as described in this report.

From a structural perspective, Massport's buildings have likely been designed to meet the minimum building code applicable at the times they were designed. While it is beyond the scope of this report to analyze the age classes of Massport buildings and historical changes to building codes over the years, it is relevant to consider that current Massachusetts State Building Code (the most stringent minimum code that has been applied in Boston to date) requires that

[11] *Note that the wind gust speed record begins in 1973 and therefore does not capture the historic event of 1954. Likewise, the peak wind gust record ends in 1995 and therefore does not capture peak wind gust speeds during Nemo in 2013.*

buildings be designed to withstand a basic wind speed of 105 mph (3-second gust), and higher wind speeds if the building's structural failure would pose a greater threat.

Any assessment of the historic frequency of 105 mph 3-second gusts and potential trends over time would require the conversion from 2-minute average wind speeds (the unit of measurement used at Logan) to 3-second wind gust speeds. WMO (2010) suggests using a "gust factor" of 1.28 for "off-sea" areas (onshore winds at a coastline) for this conversion. If the "off-sea" gust factor is applied, a 3-second gust of greater than 105 mph is estimated to have occurred only once at Logan Airport since 1945 during Hurricane Carol (discussed above), when a 2-minute average wind speed of 86 mph (110 mph 3-second gust equivalent) occurred.

Wind speed *is measured as the average wind speed of the preceding 2-minute period.*
Peak wind gust speed *is simply measured as the highest instantaneous wind speed above 25 knots (28.8 mph) since the last peak wind gust speed observation was recorded.*
Wind gust speed *is reported when the highest instantaneous wind speed in a given 10-minute period is more than 10 knots (11.5 mph) greater than the lowest "lull" in that period.*
Because of differences in reporting, the observational record for a given wind event would likely include higher peak wind gust speeds than wind gust speeds.

The next lowest wind threshold that is relevant for Massport is related to the operations of Logan Airport's Air Traffic Control Tower (Building 26). According to Massport policy, this building is evacuated when the wind gust speed reaches 78 mph.[12] Frequency analysis of both wind gust and peak wind gust data shows that such events are rare. The only record (1973-2012) of a wind gust speed reaching or exceeding 78 mph was in 2013 during Winter Storm Nemo (discussed above). Peak wind gust records (1950-1995) indicate that there were 10 days when this threshold was exceeded, six of which occurred in the 1950s. Whether the building was actually evacuated during those events could not be determined based on available information.

The long-term records for wind speeds (1945-2012) and wind gust speeds (1973-2012) at Logan Airport show statistically significant decreasing linear trends in daily average and

[12] *It is assumed that measurements of wind gust speed may have been used since 1973 and very likely after 1995 to determine when to evacuate the Air Traffic Control Tower. It is therefore relevant to assess the frequency and trends in such events using the wind gust speed record. However, it is also assumed here that measurements of peak wind gust speed may have been used prior to 1973 but certainly not after 1995 to determine when to evacuate the Air Traffic Control Tower. The peak wind gust speed record may therefore be relevant to assessing the frequency with which such events occurred historically and any trends.*

maximum wind speeds (-0.03 mph/yr) and wind gust speeds (- 0.07 mph/yr).[13] Consistent with this finding, Pryor et al. (2007, 2009, 2010) reported a declining trend in average and extreme (90^{th} percentile) wind speeds over large portions of the United States from 1973 to 2005, including the Northeast.

However, IPCC (2012, 2013) reported having low confidence in historical wind trends and their causes due to various shortcomings associated with data collection (e.g., changing locations and heights of wind measurement instruments over time), among other reasons. IPCC (2012, 2013) also reported having low confidence in future projections of changes in extreme winds because there has been relatively few studies, shortcomings in the simulation of these events, and a lack of coherence in terms of models and methods used and regions studied. For these reasons, this study has not attempted to develop quantitative projections of future wind speeds, and does not recommend that this be pursued further at this time.

Instead, this study recommends using long-term averages of daily average and maximum wind speeds and wind gust speeds. Due to wide inter-decadal variation in wind patterns, the same time period should be used for estimating these averages. Unfortunately, while wind speed records go back to 1945, wind gust speed records only began in 1973. The wind gust speed record therefore excludes important historical periods that the wind speed records include. For example, the 1950s had particularly high winds due to record Atlantic hurricane activity. Hind-casting gust speeds from 1973 to 1945 was possible because of a highly significant and well-fit correlation[14] between wind speed and wind gust speed. The historical (1945-2012) observed and estimated average and maximum wind and wind gust speeds calculated from this analysis are presented in Table 5. These values are proposed to be used by Massport as a reasonable estimate of future wind patterns, assuming that future conditions do not significantly vary from those experienced since 1945.

---

[13] *As a data quality control measure, years that have incomplete or erroneous records were excluded from the analysis and this summary. These tended to be years very early in the record, during war years, and at the end of the record.*

[14] *For annual averages of daily average wind speed and wind gust speed, $P < 0.001$, $R^2 = 0.8061$. For annual averages of daily maximum wind speed and wind gust speeds, $P < 0.001$, $R^2 = 0.5835$.*

3.6 Summary of Recommendations

Due to climate change, Logan Airport and Massport's maritime facilities in Boston Harbor will be facing increased exposure to hazards such as sea level rise, storm surge, and extreme precipitation and temperature events. This report has summarized historic and future exposure to such hazards and should be used as a foundation for climate change resiliency planning and investment at Massport moving forward, until the advancement of scientific understanding warrants an update.

Capital investments in infrastructure should take into account the likely future conditions in which it will be expected to operate within the next 20 years or more. Infrastructure risk assessment and resilience-building actions to be implemented and proposed will apply the recommendations highlighted in this report, and summarized in Table 4, as the best available information on climate hazard exposure. Table 5 provides a summary of recommended exposure values for each indicator analyzed and discussed in this report. SLOSH modeling results are discussed further in Sections 4 and 6.

Table 4 – Summary of Recommendations for Assessing Future Exposure to Climate Hazards

Climate Hazards	Recommendations for Assessing Future Exposure to Climate Hazards
Sea Level Rise	Assume 0.53 feet (6.4 inches) of sea level rise in Boston Harbor by 2033.
Storm Surge	Use the SLOSH Model to simulate storm surge heights for Category 1, 2, and 3 hurricanes hitting at different tide levels and resulting inundation. Compare inundation results against current and revised FEMA flood zone insurance rate maps.
Precipitation	Assume more frequent, more extreme precipitation events; higher average annual precipitation, mostly from increases in winter and spring; less snow (due to projected temperature increase).
Temperature	Assume more frequent, more extreme high temperature events (days greater than 90°F and 100°F) and fewer days below freezing; higher average annual temperature, mostly from increases in winter and summer.
Wind	Assume extreme wind threshold exceedances, average wind and gust speeds to remain consistent with long-term historical observations.

Table 5. Recommended Values for Climate Change Exposure Indicators

Indicator		Baseline	2018-2047 (2033s) Lower	2018-2047 (2033s) Higher	Recommended value for 2033(s)
Relative Sea Level Rise (ft.)					0.53 ft.
Storm Surge					Category 1, 2 & 3 hurricanes at different tide levels
Average Precipitation [a]	Annual precipitation (in.)	43.63	45.36	45.44	45.4 in./year
	Summer precipitation (in.)	9.63	9.20	8.97	9.1 in./year
	Winter precipitation (in.)	10.77	12.12	12.45	12.3 in./year
	Snowfall (in. liquid water equivalent)	4.80	3.65	3.70	3.7 in./year
Extreme Precipitation [a]	Average precipitation intensity (in./day)	0.92	0.96	0.96	0.96 in./day
	> 2 in. rain (days/year)	2.10	2.24	2.19	2.2 days/year
	Max. 5-day precipitation per year (in.)	5.40	6.34	6.42	6.4 in./year
Design Storms [b]	10 yr–24 hr rainfall (in)	4.91			5.6 in.
	25 yr–24 hr rainfall (in)	6.21			7.3 in.
	100 yr–24 hr rainfall (in)	8.88			10.2 in.
	10 yr–48 hr rainfall (in)	5.48			6.4 in.
	25 yr–48 hr rainfall (in)	6.97			8.6 in.
	100 yr–48 hr rainfall (in)	10.04			13.2 in.
Average Temperature [a]	Average temperature (°F)	51.3	54.8	55.0	55 °F
	Summer temperature (°F)	71.0	75.5	75.8	76 °F
	Winter temperature (°F)	31.2	34.4	35.1	35 °F
Extreme Temperature [a]	Below 32°F (days/year)	95.4	75.4	74.0	75 days/year
	Over 90°F (days/year)	10.4	29.1	31.5	30 days/year
	Over 100°F (days/year)	0.1	1.9	2.6	2.6 days/year
	Temp. exceeding runway asphalt binder operating threshold (below -18°F or Over 147°F @ 2m) (days/year)	0	0	0	0 days/year

Indicator		Baseline	2018-2047 (2033s)		Recommended value for 2033(s)
			Lower	Higher	
Wind Speed and Gust Speed [c]	Average daily wind speed (mph)	12.23			12.23 mph
	Average maximum daily wind speed (mph)	19.30			19.30 mph
	Average daily wind gust speed (mph) - estimated	26.10			26.10 mph
	Average maximum daily wind gust speed (mph) - estimated	29.91			29.91 mph
	Maximum 3-second gust speed (mph) - estimated	110			110 mph
	Maximum 2-minute wind speed (mph)	86			86 mph
Wind Thresholds	Wind speed ≥ 40 mph (days/year) (high wind) [c]	2.3			2.3 days/year
	Peak wind gust ≥ 78 mph (days/year) (ATC Tower evacuation) [d]	0.2			0.2 days/year
	3-second gust ≥ 105 mph (days/year) (basic wind speed from MA building code) [c e]	0.01			0.01 days/year

[a] Baseline for Average and Extreme Precipitation and Temperature indicators is 1971-2000. Recommended values for Average and Extreme Precipitation and Temperature are averages between the high and low values for the 2033s, except for days over 100°F, which is the high value.

[b] Baseline for Design Storms is from Northeast Regional Climate Center.

[c] Baseline for Wind Speed and estimated Gust Speed is 1945-2012.

[d] Baseline for Peak Wind Gust is 1950-1995.

[e] The frequency of 3-second gust speeds exceeding 105 mph is calculated based on Wind Speed conversions as described in this report.

4. METHODOLOGY FOR SELECTING DESIGN FLOOD ELEVATIONS

4.1 Design Flood Elevations

The purpose of this section is to explain the criteria used to develop design flood elevations at Logan Airport and the maritime facilities in South Boston. These design flood elevations were then used to inform resiliency recommendations for critical assets at these facilities as part of the Massport DIRP study. The criteria used included the following:

- Storm surge elevations determined using the SLOSH model
- Historical occurrence of hurricanes in the Boston Harbor region
- Variability of past storm events, including nor'easters and hurricanes, based on storm intensity, frequency and tidal elevation
- Sea level rise and storm intensification considerations
- Consideration of current and proposed FEMA Base Flood Elevations (BFEs)

The storm surge types that were evaluated to determine the design flood elevation for Massport were based on discussions with Massport as part of regular project coordination meetings, meetings with the Massport executive committee, as well as the March 2014 Massport Board of Directors Meeting. The proposed design flood elevations that were selected for adaptation recommendations for Logan Airport and maritime facilities in South Boston were finalized in a meeting on April 30, 2014 with the Massport executive committee (Mr. Houssam Sleiman, Director for Capital Programs and Environmental Affairs, Dr. Luciana Burdi, Deputy Director for Capital Programs and Environmental Affairs, and Ms. Robbin Peach, Program Manager of Resiliency , Capital Program and Environmental Affairs) and the project team.

Figure 9 below represents the flood elevations that were proposed for retrofitting existing buildings at Logan Airport, and Figure 10 represents the flood elevations for retrofitting of existing buildings for maritime facilities in South Boston.

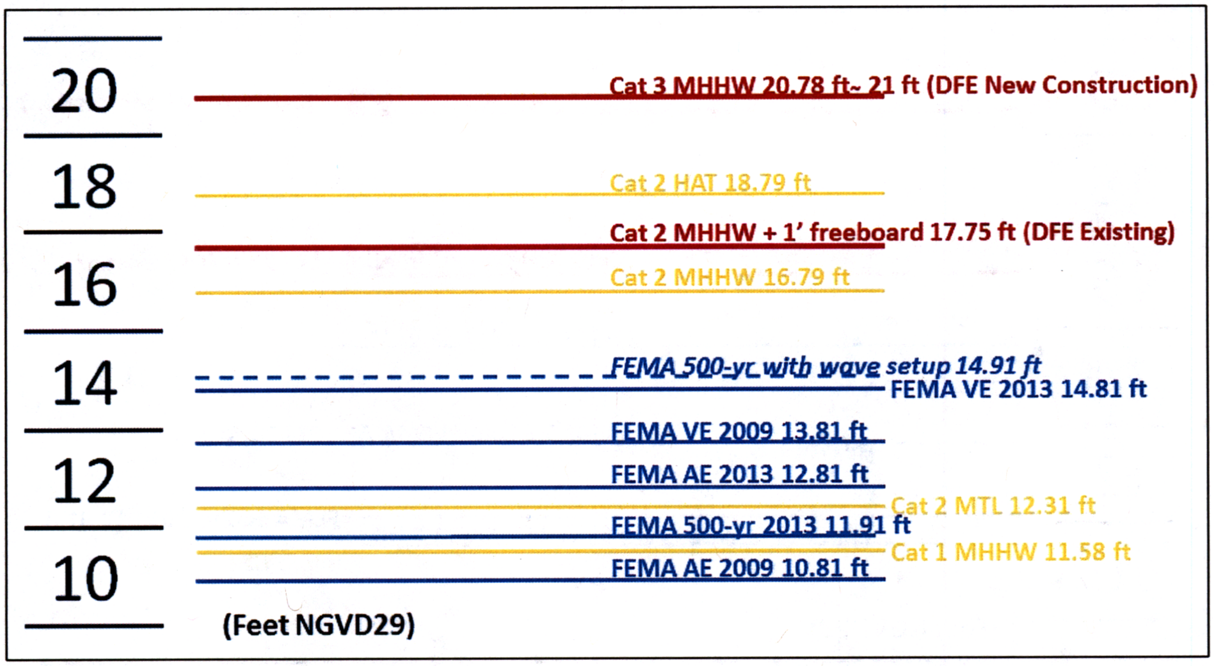


Figure 9 – Flood Elevations at Logan Airport to Determine the Design Flood Elevation (DFE)

Notes: *1. Hurricane elevations are based on maximum surge elevation for all critical facilities across Logan for present day. 2. Elevations are based on datum NGVD29 and lines showing elevations are approximately to scale. 3. For retrofitting existing infrastructure in Logan, DFE is the maximum surge elevation from a worst-possible Category 2 hurricane at MHHW + 1 ft freeboard, rounded down to 17.75 ft NGVD29. For new construction in Logan, DFE is the maximum surge elevation from a worst-possible Category 3 hurricane at MHHW.*

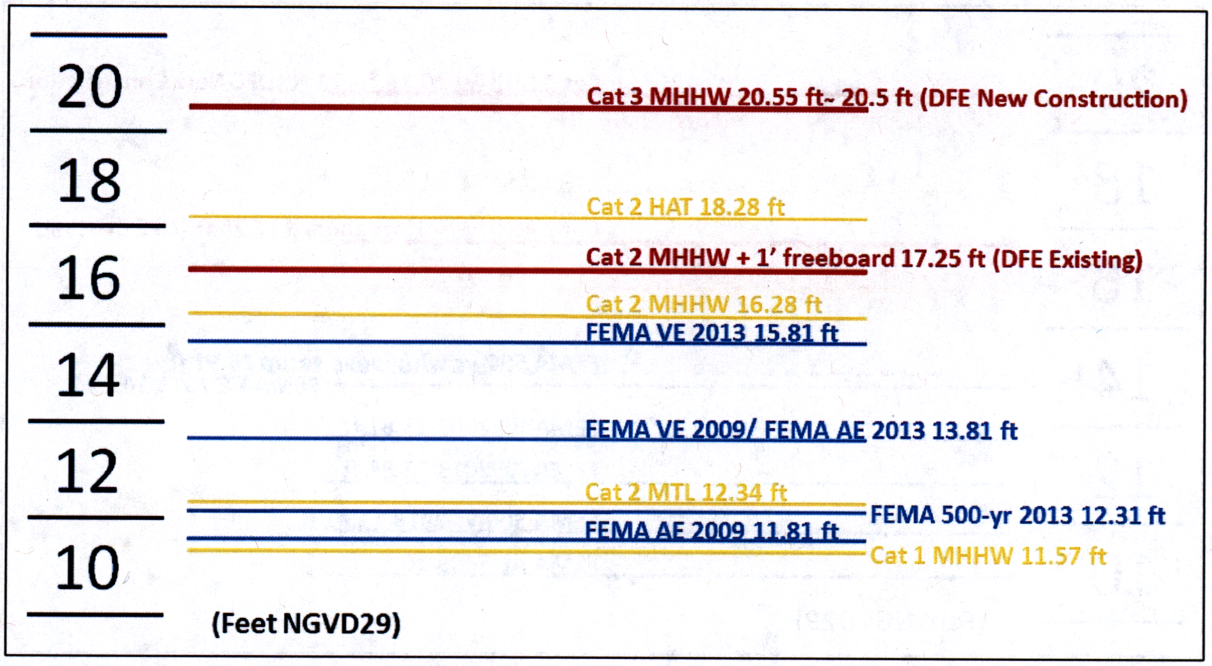


Figure 10 – Flood Elevations at Maritime Facilities in South Boston to Determine the Design Flood Elevation (DFE)

Notes: *1. Hurricane elevations are based on maximum surge elevation for all critical facilities across maritime facilities in South Boston. 2. Elevations are based on datum NGVD29 and lines showing elevations are to scale approximately. 3. For retrofitting existing infrastructure at maritime facilities in South Boston, DFE is the maximum surge elevation from a worst-possible Category 2 hurricane at MHHW + 1 ft freeboard, rounded down to 17.25 ft NGVD29. For new construction at maritime facilities in South Boston, DFE is the maximum surge elevation from a worst-possible Category 3 hurricane at MHHW, rounded down to 20.5 ft NGVD29.*

Logan Design Considerations

A Design Flood Elevation (DFE) of 17.75 ft NGVD29 is proposed for retrofitting existing buildings at Logan Airport. This is based on considering the following criteria:

- Maximum storm surge elevation of 16.79 ft NGVD29 among all critical facilities in Logan experienced from the worst-possible Category 2 hurricane (e.g. track line resulting in a direct hit, a radius of maximum winds that results in the most damage, an intense central pressure, etc.) making landfall today.
- The Category 2 hurricane was simulated at the mean higher high water (MHHW) tidal cycle in Boston Harbor.

- Since SLOSH does not account for wave processes, a freeboard of 1 ft was considered as a conservative contingency to account for uncertainties associated with wave dynamics and the model itself. These considerations yielded a DFE of 17.79 ft NGVD29, which was rounded down to 17.75 ft NGVD29

A DFE of 21 ft NGVD29 is proposed for construction of new buildings at Logan Airport. This is based on considering the following criteria:

- Maximum storm surge elevation of 20.78 ft NGVD29 among all critical facilities in Logan experienced from the worst-possible Category 3 hurricane (e.g. track line resulting in a direct hit, a radius of maximum winds that results in the most damage, an intense central pressure, etc.) making landfall today.
- The Category 3 hurricane was simulated at the mean higher high water (MHHW) tidal cycle in Boston Harbor
- No freeboard was added since the proposed storm surge elevation that could be experienced from the worst-possible Category 3 hurricane hitting at MHHW is a very unlikely event and is significantly higher than what has been experienced in past events.

Maritime Facilities Design Considerations

A DFE of 17.25 ft NGVD29 is proposed for retrofitting existing buildings at maritime facilities in South Boston. This is based on considering the following criteria:

- Maximum storm surge elevation of 16.28 ft NGVD29 among all critical maritime facilities in South Boston experienced from the worst-possible Category 2 hurricane e.g. track line resulting in a direct hit, a radius of maximum winds that results in the most damage, an intense central pressure, etc.) making landfall today.
- The Category 2 hurricane was simulated at the mean higher high water (MHHW) tidal cycle in Boston Harbor.
- Since SLOSH does not account for wave processes, a freeboard of 1 ft is considered as a conservative contingency to account for uncertainties associated with wave dynamics and the model itself; this yields 17.29 ft NGVD29, which was rounded down to 17.25 ft NGVD29.

A DFE of 20.5 ft NGVD29 is proposed for construction of new buildings at maritime facilities in South Boston. This is based on considering the following criteria:

- Maximum storm surge elevation of 20.56 ft NGVD29 among all critical facilities in South Boston Maritime experienced from the worst-possible Category 3 hurricane e.g. track line resulting in a direct hit, a radius of maximum winds that results in the most damage, an intense central pressure, etc.) making landfall today.
- The Category 3 hurricane was simulated at the mean higher high water (MHHW) tidal cycle at Boston Harbor.
- No freeboard was added since the proposed storm surge elevation that could be experienced from the worst-possible Category 3 hurricane hitting at MHHW is a very unlikely event and is significantly higher than what has been experienced in past events.

The following disclaimers apply when considering the above proposed design flood elevations:

- The design flood elevations are based on reasonable estimates of maximum storm surge elevations based on best available model information using the SLOSH model.
- The predicted surge elevations from SLOSH do not include wave set-up on top of the surge. The SLOSH model does not account for wave processes, such as wave propagation, wave heights, etc.
- The predicted surge elevations from SLOSH do not account for increased overland flooding due to rainfall.
- Sea level rise is projected to rise by 0.53 ft (2012 NOAA NCA "Intermediate High" scenario) by 2033, which is a small fraction compared to the worst-possible storm surge elevations that have been considered. This rise is accommodated within the proposed DFEs; therefore, no additional adjustments were made for sea level rise in the design flood elevations.
- SLOSH is an event-based model that is used to estimate storm surge elevations from historical, hypothetical and predicted hurricanes. It does not model the probability of surge elevations being reached. The Boston Harbor Flood Risk Model (BH-FRM) using the ADCIRC model that is currently being developed for the Massachusetts Department of Transportation (MassDOT) and Federal Highway Administration (FHWA) project by the Woods Hole Group will provide probability information that can be combined with the event-driven data of SLOSH to further inform design considerations. The ADCIRC modeling is outside of the scope of this current project and would need to be considered separately.

4.2 Storm Surge Modeling Conducted Using the SLOSH Model

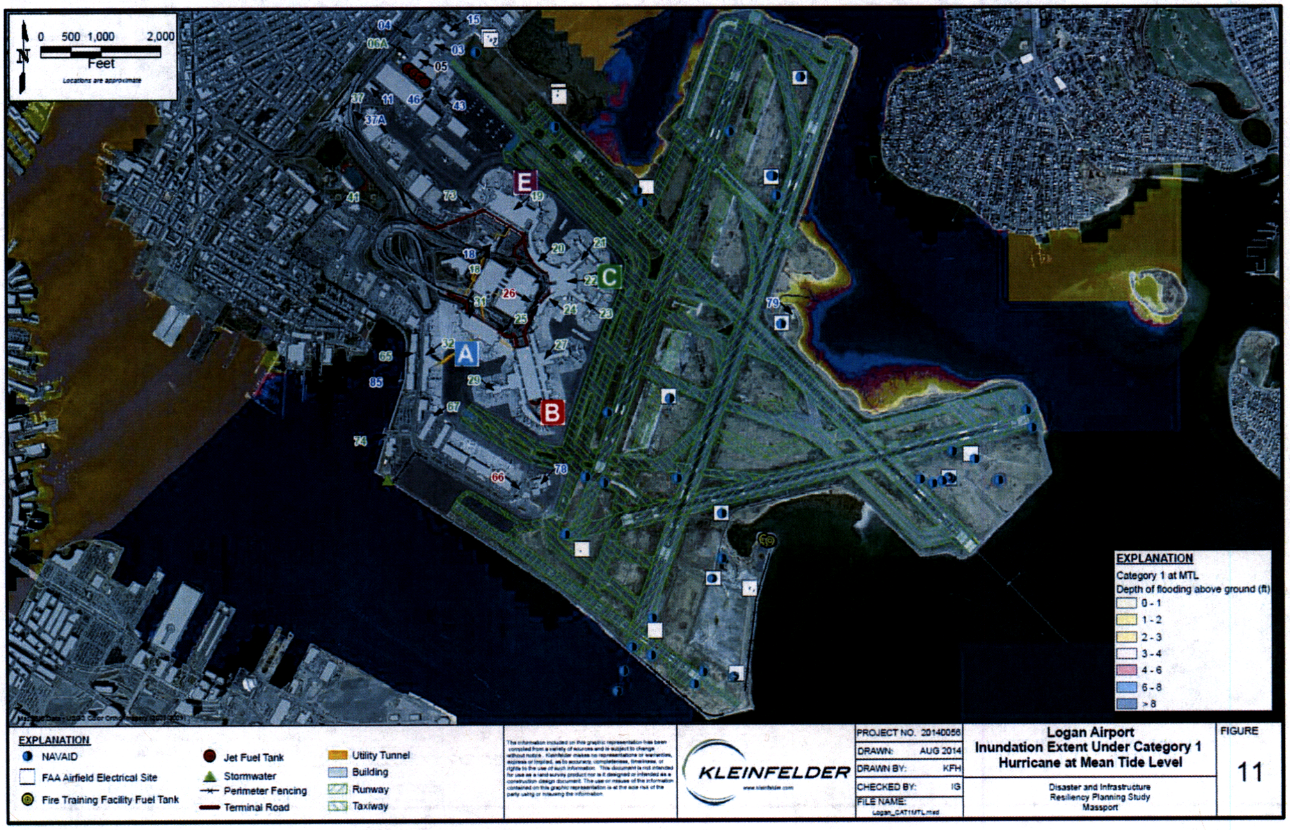
The storm surge model used in this project is the hydrodynamic Sea, Lake, and Overland Surge from Hurricanes (SLOSH) Model developed by the National Weather Service. SLOSH is a computer model used to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. The National Weather Service has generated composites of several thousand runs of hypothetical hurricanes in the SLOSH model, which have been categorized as MEOWs (Maximum Envelopes of Water) or MOMs (Maximum(s) of the MEOWs). The MEOW is the composite set of highest storm surge values at each grid location for a given storm category, forward speed, and direction of motion. The MOM is the Maximum of the MEOWs, which represents the worst combination of hurricane landfall location, forward speed and direction for given hurricane category for a given tidal elevation at every grid cell.

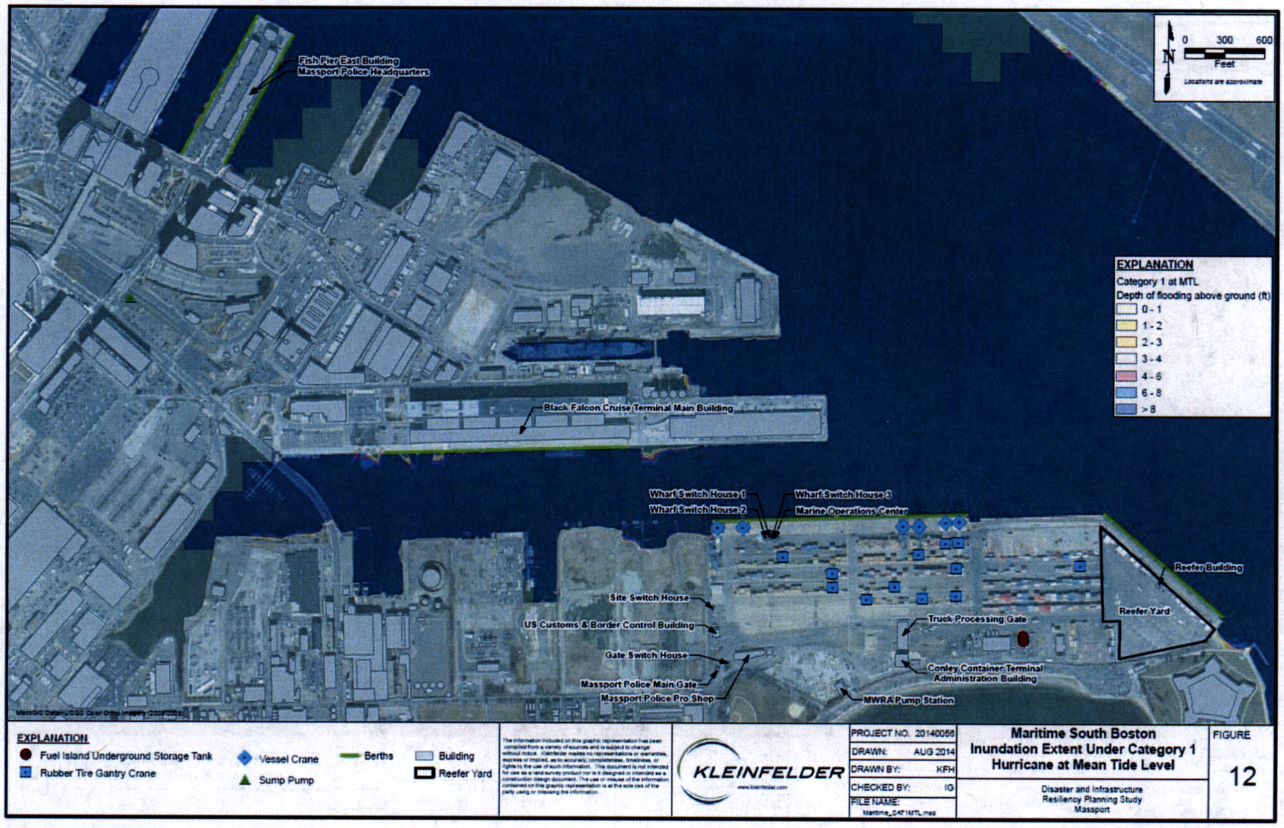
The MOM simulations were chosen for both Category 2 and 3 hurricanes for Logan Airport and maritime facilities in South Boston using the SLOSH basin for Boston Harbor/Providence (pv2 basin). The MOM simulations were selected because the National Hurricane Center recommends using the MOM surge values for planning purposes when hurricane landfall is greater than 120 hours away (http://www.nhc.noaa.gov/surge/products.php). It is important to note that the storm surge elevations, as reported by the MOM simulation, say, for the Category 2 hurricane at mean higher high water, are *not* caused due to *one* particular Category 2 hurricane but due to a *composite* of several thousand Category 2 hurricane runs with the worst-possible combination of landfall location, forward speed and hurricane track direction.

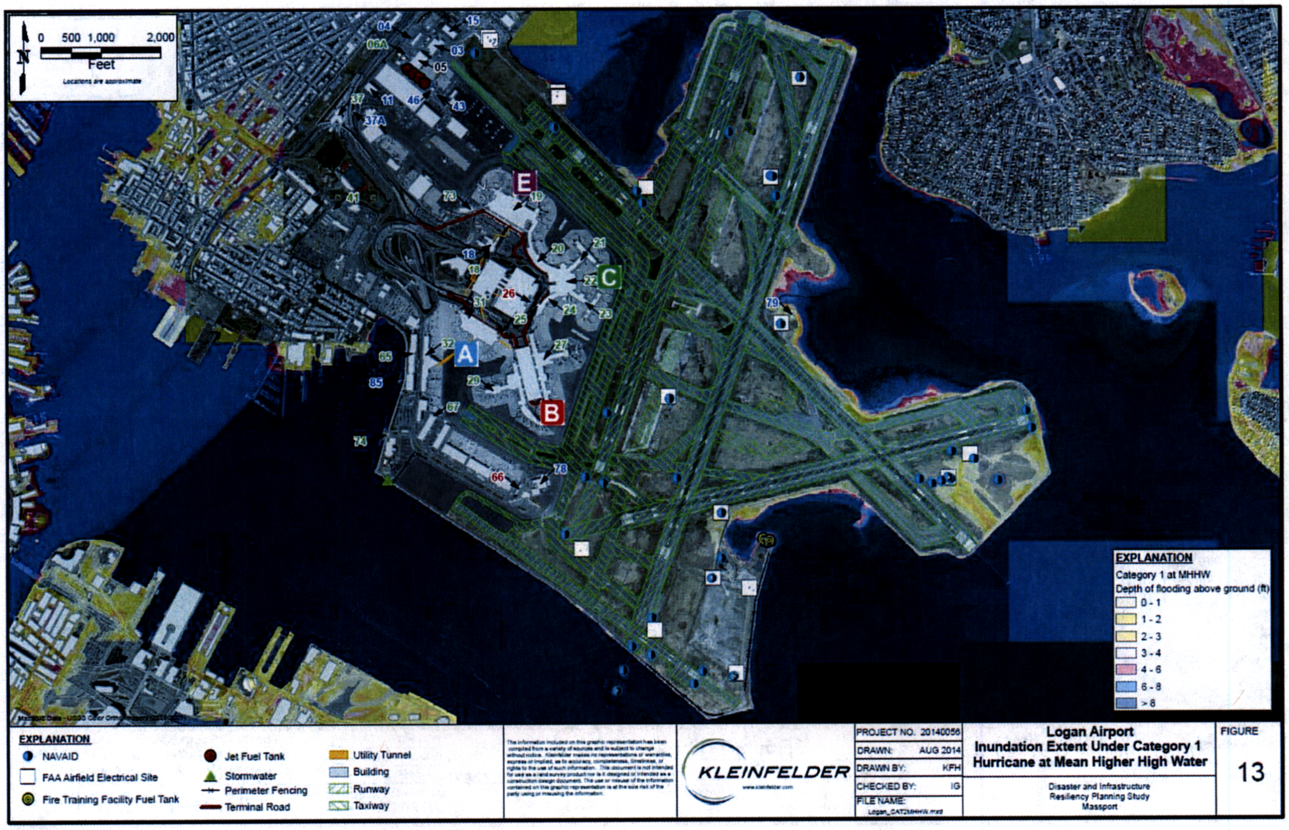
The SLOSH model simulations, using the MOM for each category were conducted for Logan and the maritime facilities in South Boston were conducted under the following scenarios:

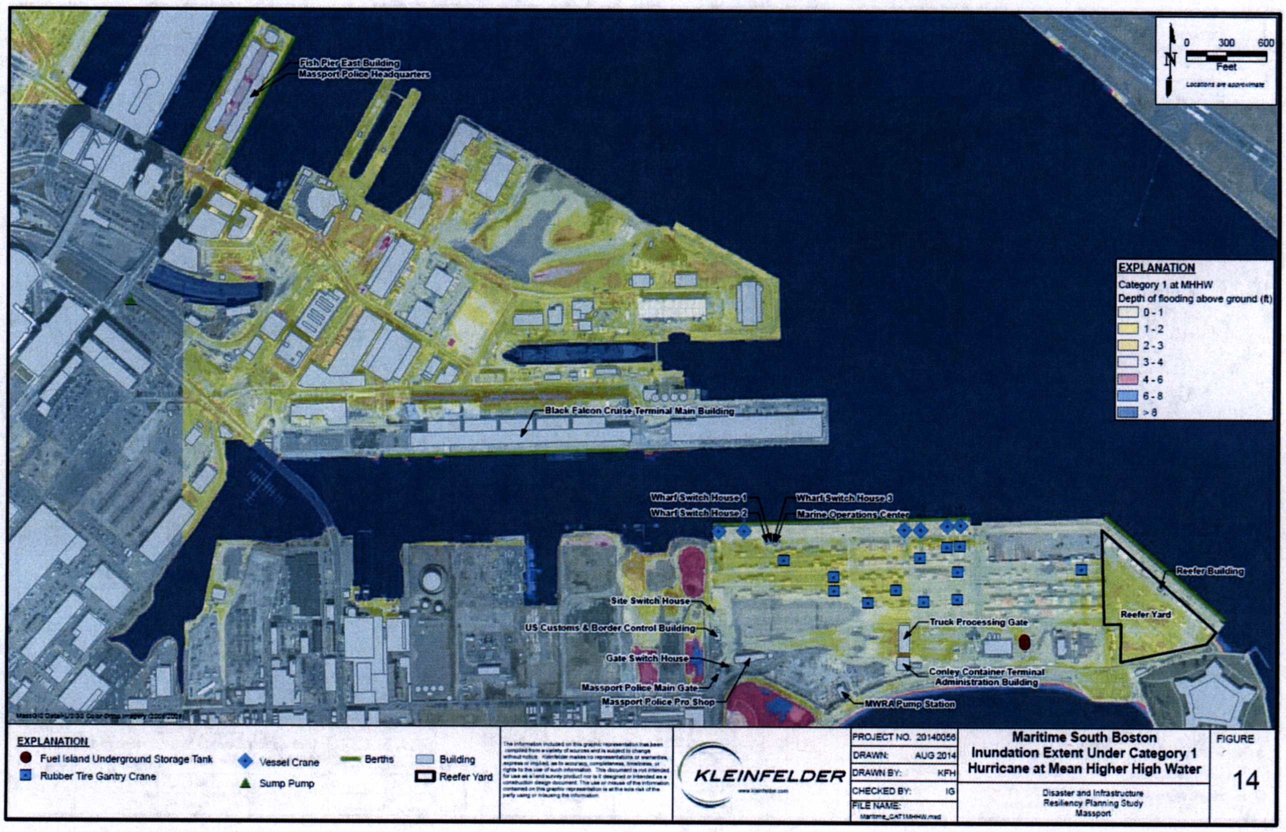
- Category 1 hurricane at mean tide level (MTL)
- Category 1 hurricane at mean higher high water (MHHW)
- Category 2 hurricane at MTL
- Category 2 hurricane at MHHW
- Category 3 hurricane at MHHW

For the MHHW runs, the depth of inundation was determined by spatially overlaying (using GIS) the hurricane surge heights from the SLOSH MOM model runs for each grid cell with MHHW tidal elevation surface for the Boston Harbor area (MHHW tidal elevation varies from 5.45 ft to 5.65 ft NGVD29) obtained from the Massachusetts Coastal Zone Management, and with the LiDAR elevation data obtained from the 2009 Boston (horizontal accuracy 1 ft, vertical accuracy 0.2 ft) and the 2010 Quincy (horizontal accuracy 3.28 ft, vertical accuracy 0.19 ft) LiDAR datasets. The SLOSH model surge elevations have, in general, an accuracy of +/- 20%. However, for the pv2 SLOSH basin, the SLOSH accuracy was found to vary within -7% and +25% based on comparison of observed surge (at the NOAA Boston Harbor tidal gage) and simulated surge values (using SLOSH) for three historical hurricanes (1938 Great New England Hurricane Category 2, Great Atlantic Hurricane of 1944 Category 1 and Hurricane Carol Category 2). The results of the SLOSH simulations for the five scenarios above for Logan and Maritime have been presented in Figures 11 through 20.


0 500 1,000 2,000
Feet
Locations are approximate
N
A
B
C
E
EXPLANATION
Category 1 at MTL
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
NAVAID
FAA Airfield Electrical Site
Fire Training Facility Fuel Tank
Jet Fuel Tank
Stormwater
Perimeter Fencing
Terminal Road
Utility Tunnel
Building
Runway
Taxiway
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Logan_CAT1MTL.mxd
Logan Airport
Inundation Extent Under Category 1
Hurricane at Mean Tide Level
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
11

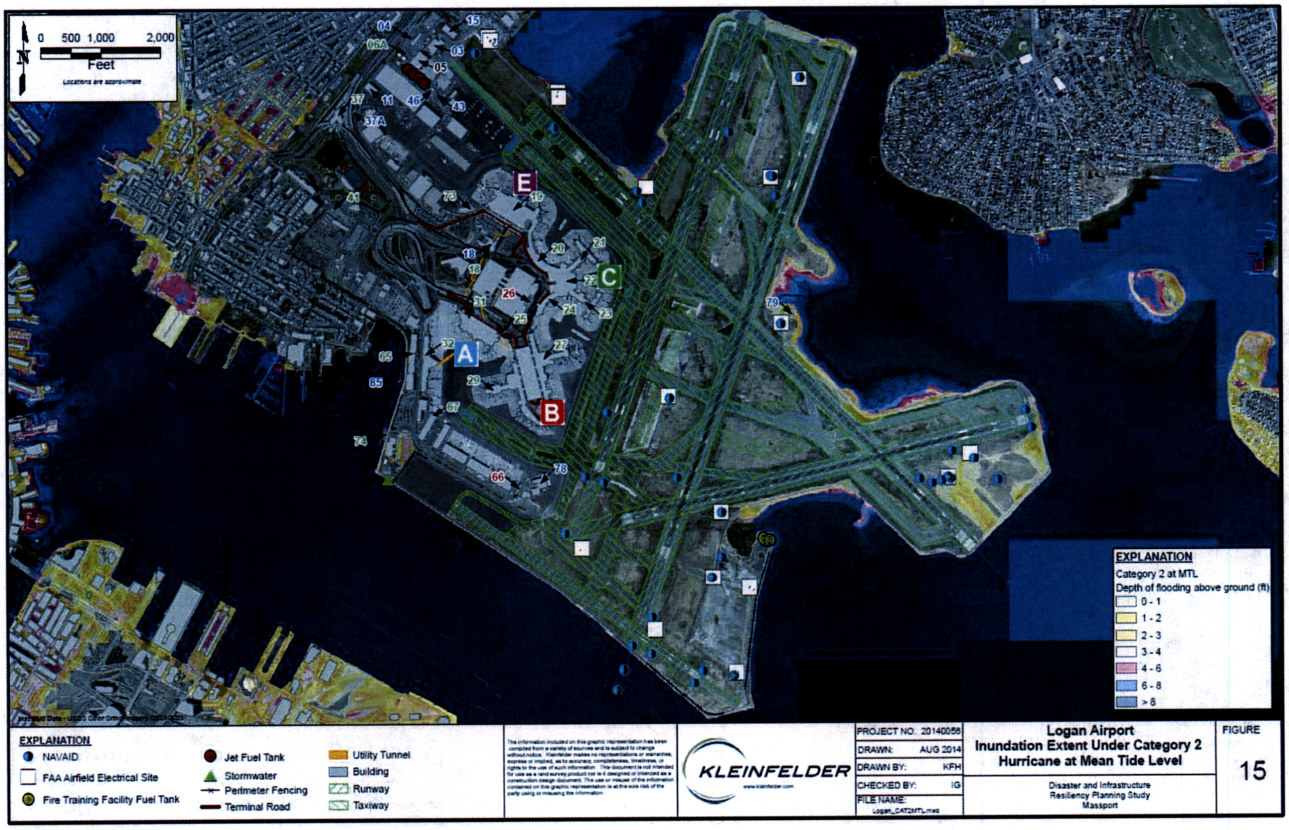

Fish Pier East Building
Massport Police Headquarters
Black Falcon Cruise Terminal Main Building
Wharf Switch House 1
Wharf Switch House 2
Wharf Switch House 3
Marine Operations Center
Site Switch House
US Customs & Border Control Building
Gate Switch House
Massport Police Main Gate
Massport Police Pro Shop
MWRA Pump Station
Truck Processing Gate
Conley Container Terminal Administration Building
Reefer Building
Reefer Yard
0 300 600
Feet
Locations are approximate
N
EXPLANATION
Category 1 at MTL
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
Fuel Island Underground Storage Tank
Rubber Tire Gantry Crane
Vessel Crane
Sump Pump
Berths
Building
Reefer Yard
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Maritime South Boston
Inundation Extent Under Category 1
Hurricane at Mean Tide Level
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
12

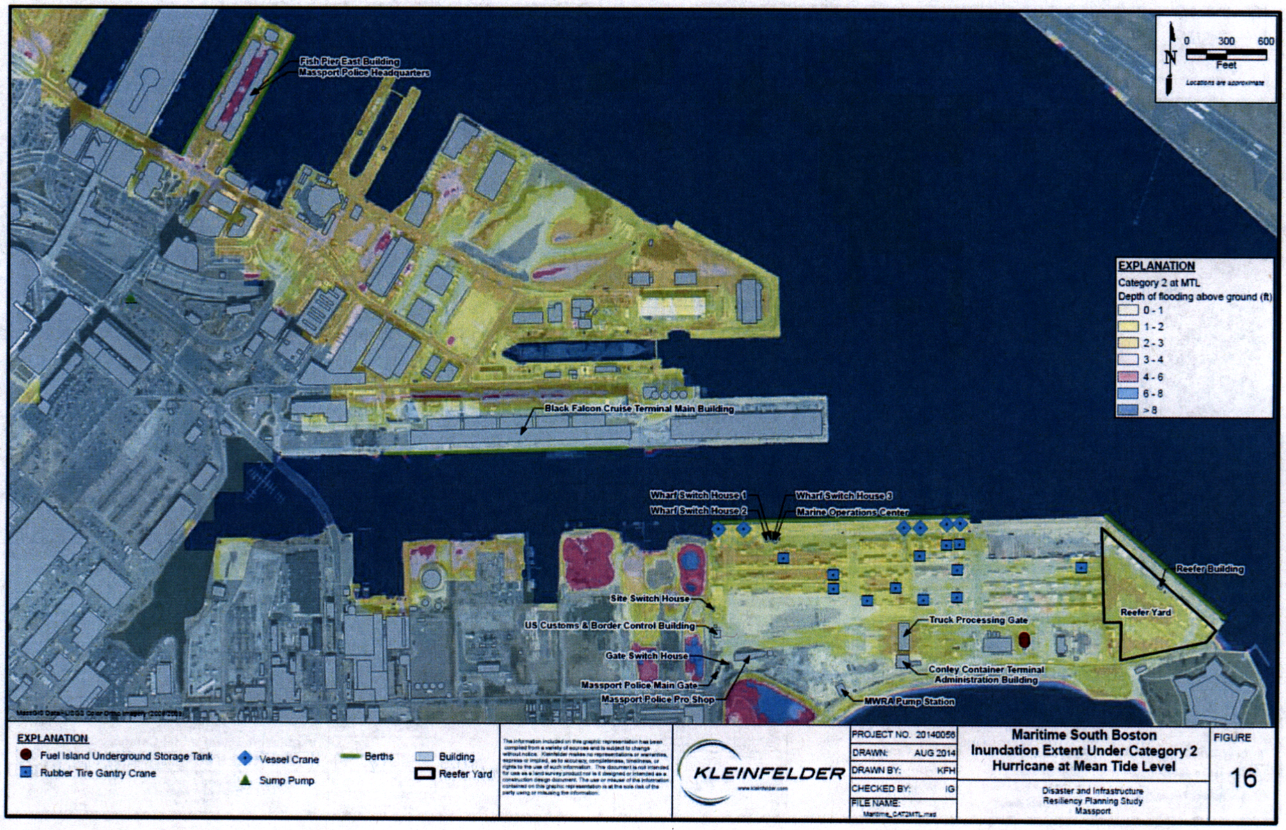

0 500 1,000 2,000
Feet
N
EXPLANATION
Category 1 at MHHW
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
A
B
C
E
EXPLANATION
NAVAID
FAA Airfield Electrical Site
Fire Training Facility Fuel Tank
Jet Fuel Tank
Stormwater
Perimeter Fencing
Terminal Road
Utility Tunnel
Building
Runway
Taxiway
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Logan Airport
Inundation Extent Under Category 1
Hurricane at Mean Higher High Water
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
13

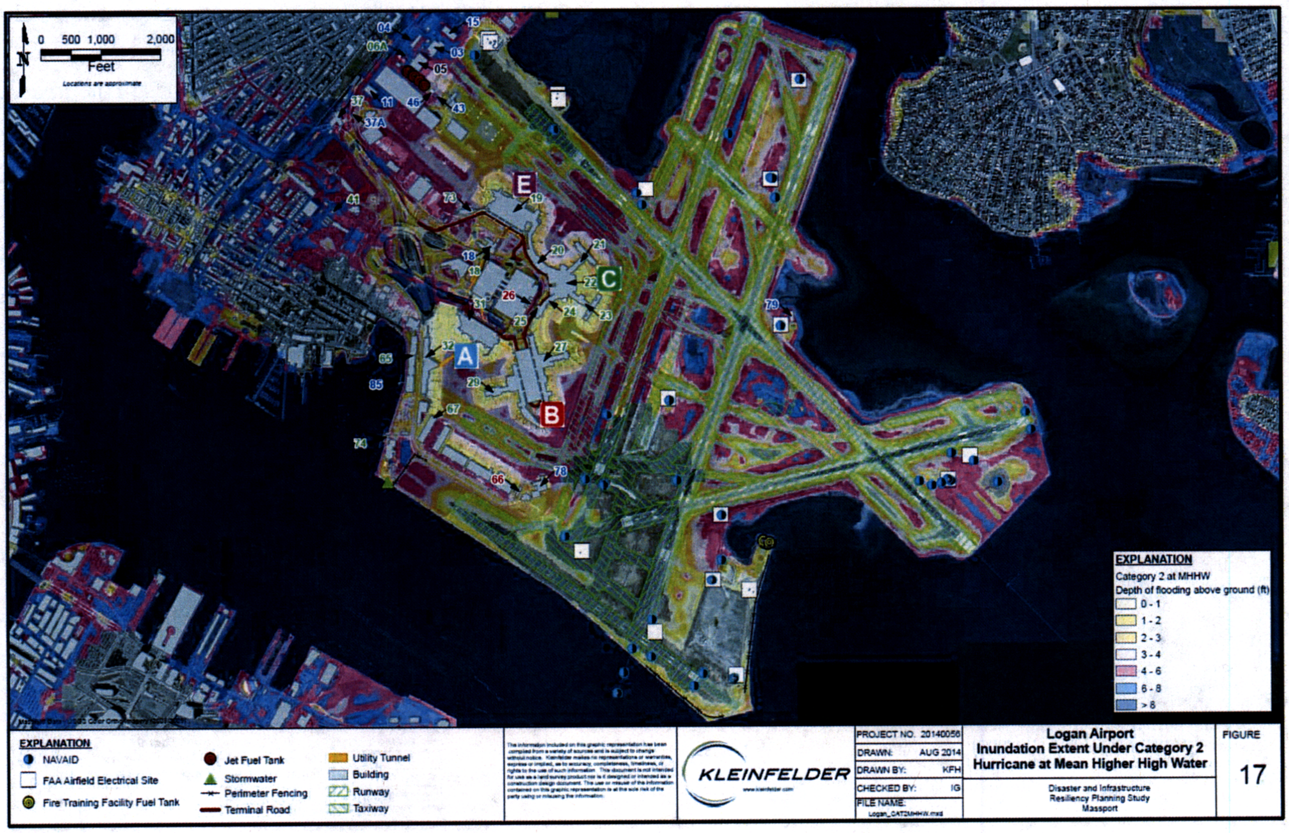


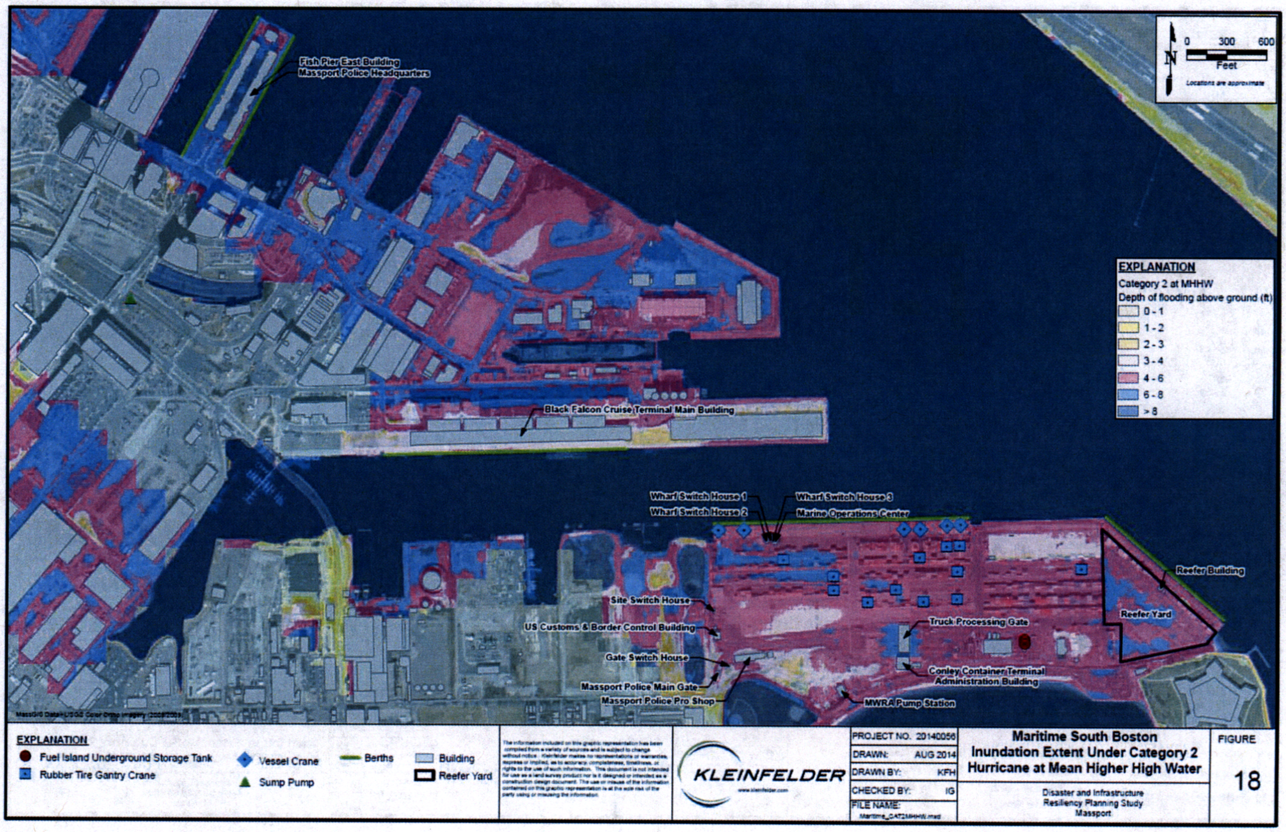
Maritime South Boston
Inundation Extent Under Category 1
Hurricane at Mean Higher High Water

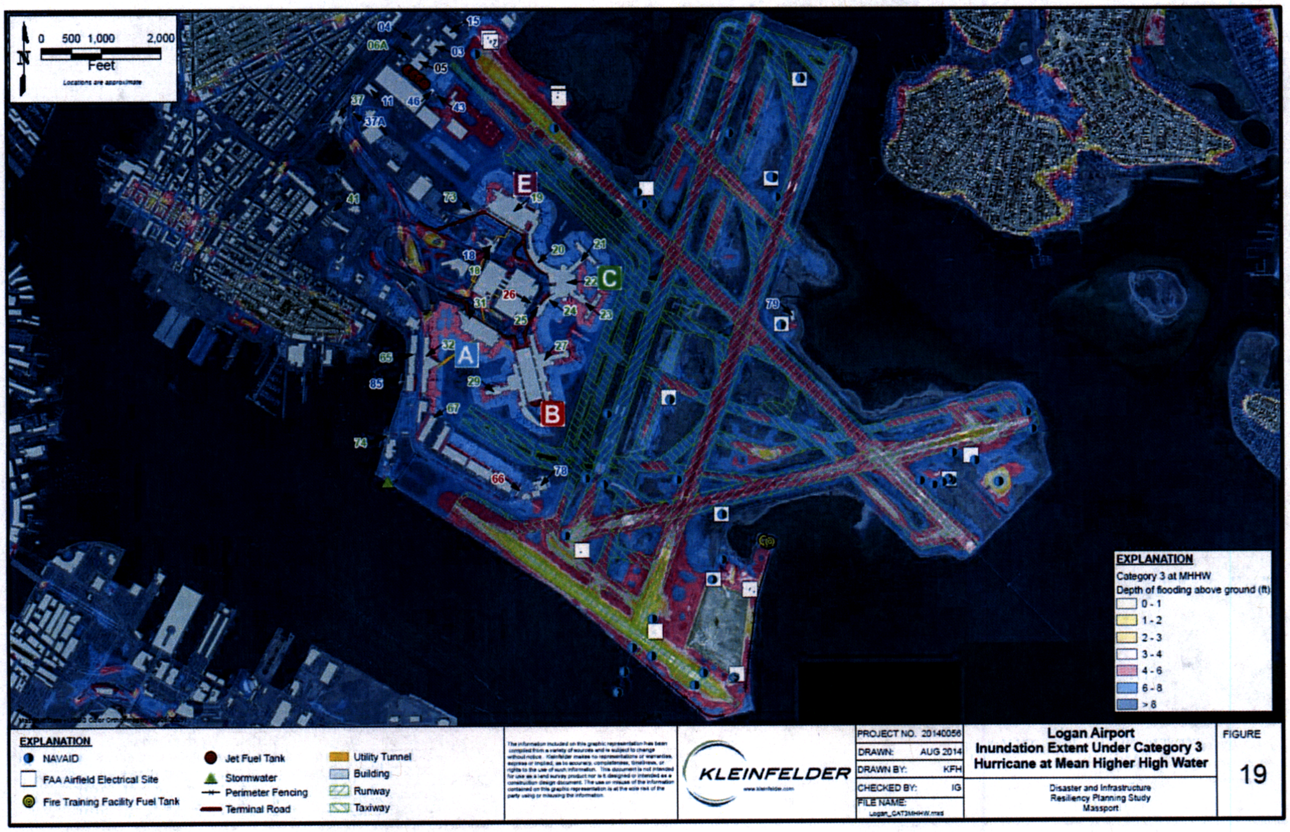
FIGURE 14

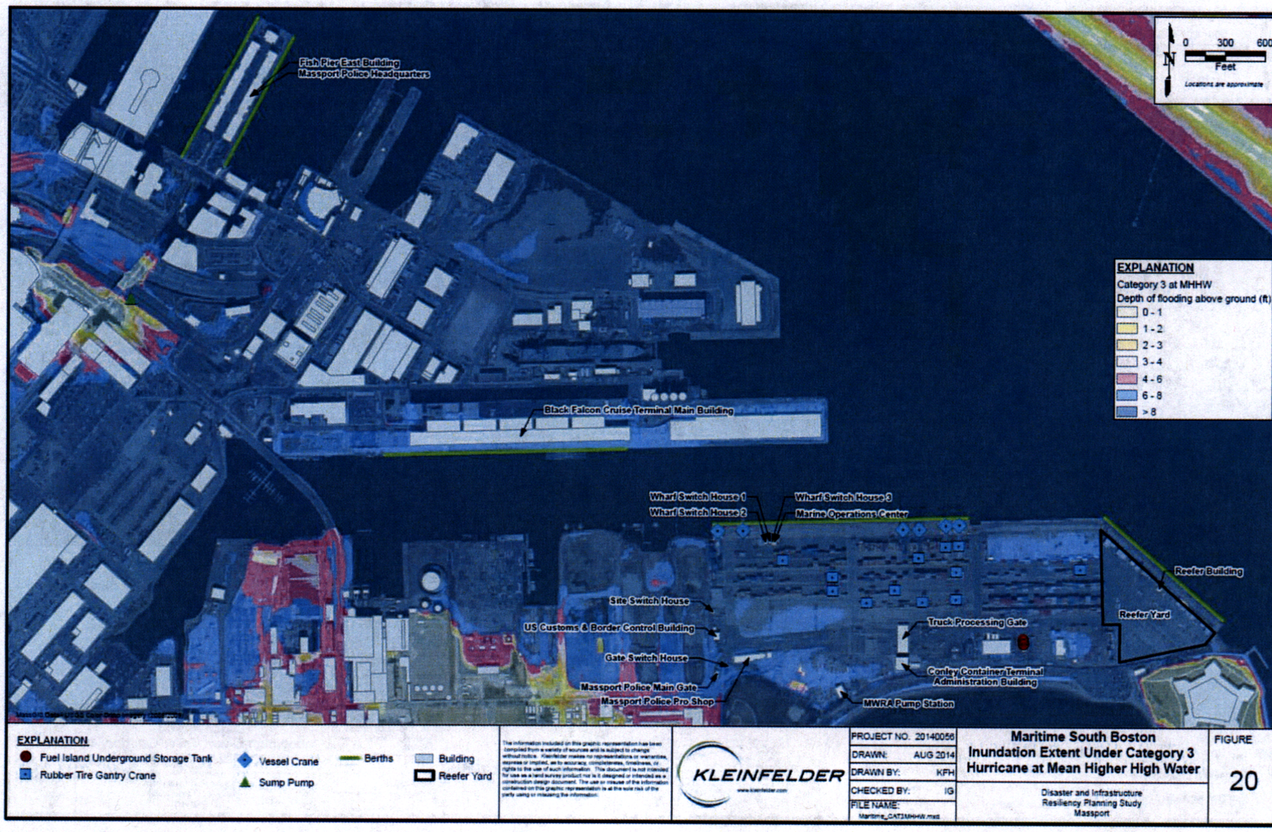

0 500 1,000 2,000
Feet
Locations are approximate
N
A
B
C
E
EXPLANATION
Category 2 at MTL
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
NAVAID
FAA Airfield Electrical Site
Fire Training Facility Fuel Tank
Jet Fuel Tank
Stormwater
Perimeter Fencing
Terminal Road
Utility Tunnel
Building
Runway
Taxiway
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Logan Airport
Inundation Extent Under Category 2
Hurricane at Mean Tide Level
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
15


Fish Pier East Building
Massport Police Headquarters
Black Falcon Cruise Terminal Main Building
Wharf Switch House 1
Wharf Switch House 2
Wharf Switch House 3
Marine Operations Center
Reefer Building
Reefer Yard
Site Switch House
US Customs & Border Control Building
Truck Processing Gate
Gate Switch House
Massport Police Main Gate
Massport Police Pro Shop
Conley Container Terminal Administration Building
MWRA Pump Station
0 300 600
Feet
N
Locations are approximate
EXPLANATION
Category 2 at MTL
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
Fuel Island Underground Storage Tank
Rubber Tire Gantry Crane
Vessel Crane
Sump Pump
Berths
Building
Reefer Yard
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Maritime South Boston
Inundation Extent Under Category 2
Hurricane at Mean Tide Level
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
16


0 500 1,000 2,000
N
Feet
Locations are approximate
A
B
C
E
EXPLANATION
Category 2 at MHHW
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
NAVAID
FAA Airfield Electrical Site
Fire Training Facility Fuel Tank
Jet Fuel Tank
Stormwater
Perimeter Fencing
Terminal Road
Utility Tunnel
Building
Runway
Taxiway
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME: Logan_CAT2MHHW.mxd
Logan Airport
Inundation Extent Under Category 2
Hurricane at Mean Higher High Water
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
17


Fish Pier East Building
Massport Police Headquarters
Black Falcon Cruise Terminal Main Building
Wharf Switch House 1
Wharf Switch House 2
Wharf Switch House 3
Marine Operations Center
Reefer Building
Reefer Yard
Site Switch House
US Customs & Border Control Building
Truck Processing Gate
Gate Switch House
Conley Container Terminal
Administration Building
Massport Police Main Gate
Massport Police Pro Shop
MWRA Pump Station
0 300 600
Feet
EXPLANATION
Category 2 at MHHW
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
Fuel Island Underground Storage Tank
Rubber Tire Gantry Crane
Vessel Crane
Sump Pump
Berths
Building
Reefer Yard
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Maritime South Boston
Inundation Extent Under Category 2
Hurricane at Mean Higher High Water
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
18


0 500 1,000 2,000
Feet
Locations are approximate
N
A
B
C
E
EXPLANATION
Category 3 at MHHW
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
EXPLANATION
NAVAID
FAA Airfield Electrical Site
Fire Training Facility Fuel Tank
Jet Fuel Tank
Stormwater
Perimeter Fencing
Terminal Road
Utility Tunnel
Building
Runway
Taxiway
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Logan_CAT3MHHW.mxd
Logan Airport
Inundation Extent Under Category 3
Hurricane at Mean Higher High Water
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
19


Fish Pier East Building
Massport Police Headquarters
0 300 600
Feet
Locations are approximate
EXPLANATION
Category 3 at MHHW
Depth of flooding above ground (ft)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 6
6 - 8
> 8
Black Falcon Cruise Terminal Main Building
Wharf Switch House 1
Wharf Switch House 2
Wharf Switch House 3
Marine Operations Center
Reefer Building
Reefer Yard
Site Switch House
US Customs & Border Control Building
Truck Processing Gate
Gate Switch House
Massport Police Main Gate
Massport Police Pro Shop
Conley Container Terminal
Administration Building
MWRA Pump Station
EXPLANATION
Fuel Island Underground Storage Tank
Rubber Tire Gantry Crane
Vessel Crane
Sump Pump
Berths
Building
Reefer Yard
KLEINFELDER
PROJECT NO. 20140056
DRAWN: AUG 2014
DRAWN BY: KFH
CHECKED BY: IG
FILE NAME:
Maritime_CAT3MHHW.mxd
Maritime South Boston
Inundation Extent Under Category 3
Hurricane at Mean Higher High Water
Disaster and Infrastructure
Resiliency Planning Study
Massport
FIGURE
20

In addition to MTL and MHHW tidal conditions, the following scenarios were also evaluated:

- Category 1 hurricane at mean low water (MLW)
- Category 2 hurricane at mean low water (MLW)

Since SLOSH model simulations for MLW are not available from NOAA and National Hurricane Center (NHC), we used an approximation method to determine the flood elevations under this scenario. Flood elevations were determined by subtracting 4.75 ft (i.e., the difference between the MTL 0.39 ft NGVD29 and MLW -4.36 ft NGVD29) from the corresponding flood elevations at MTL (available from SLOSH runs) for each facility.

Storm surge elevations at each critical facility/building for all the seven scenarios were identified using GIS. Tables 6a-c and Table 7 report flood elevations (above NGVD29, based on SLOSH) and estimated depth of flooding above first floor for Logan and Maritime South Boston infrastructure under Cat 1 MHHW, Cat 2 MTL and MHHW, and Category 3 MHHW scenarios. These tables indicate where flooding above first floor elevation is reported based on SLOSH model results, as well as where no flooding is reported above first floor. These tables do not include elevations or flood depths for Category 1 and Category 2 hurricanes at MLW and Category 1 hurricane at MTL because no flooding of critical facilities/buildings was observed for these scenarios. Estimated flood depths are based on readily available first floor elevation data (e.g., from engineering plans). However, detailed surveys were not conducted, and therefore, this data may contain inaccuracies. More details on sources of data and methods used are provided in Section 6.1.

Table 6a – Flood Elevations and Depths for Logan Facilities

No.	Name	Flood Elevations (Elev) and Flood Depth Above First Floor (Depth)*							
		CAT 1 MHHW		CAT 2 MTL		CAT 2 MHHW		CAT 3 MHHW	
		Elev	Depth	Elev	Depth	Elev	Depth	Elev	Depth
		(ft NGVD29)	(ft)	(ft NGVD29)	(ft)	(ft NGVD29)	(ft)	(ft NGVD29)	(ft)
41	Porter Street Substation	NA	NA	NA	NA	16.4	4.61	20.7	8.91
67	Bird Island Flats Substation	NA	NA	NA	NA	16.18	0.64	20.46	4.92
2	Wood Island Substation	NA	NA	NA	NA	16.79	4.83	20.78	8.82
32	Harborside Substation	NA	NA	NA	NA	16.19	NA	20.51	4.2
65	Logan Office Center	NA	NA	NA	NA	16.18	2.09	20.5	6.41
26	Air Traffic Control Tower[1]	NA	NA	NA	NA	16.18	4	20.48	8.3
26	Control Tower Substation[2]	NA	NA	NA	NA	16.18	2.92	20.48	7.22
26	MPA Generator - Control Tower[2]	NA	NA	NA	NA	16.18	6.07	20.48	10.37
25	MPA Administration Building (Old Tower)	NA	NA	NA	NA	16.18	0.28	20.48	4.58
25	MPA Administration Building (Boutwell/Pier D)	NA	NA	NA	NA	16.18	0.78	20.48	5.08
3	Facilities II	NA	NA	NA	NA	16.79	5.22	20.77	9.2
4	Facilities III	NA	NA	NA	NA	16.78	1.18	20.78	5.18
15	Large Vehicle Storage Building	NA	NA	NA	NA	16.79	4.83	20.78	8.82
	West Outfall (bar screen bldg)[2]	NA	NA	NA	NA	16.28	5.03	20.38	9.13
	West Outfall (electrical)[2]	NA	NA	NA	NA	16.28	2.33	20.38	6.43
78	Fire-Rescue I	NA	NA	NA	NA	15.98	0.87	20.3	5.19
79	Fire-Rescue II	11.46	0.61	11.81	0.96	15.76	4.91	19.92	9.07
85	Marine Fire-Rescue	11.58	0.17	12.31	0.90	16.18	4.77	20.46	9.05
	Fire Training Facility fuel tanks	NA	NA	NA	NA	15.76	0.95	19.72	4.91
18	Central Heating Plant/Facilities I	NA	NA	NA	NA	16.17	1.68	20.68	6.19
11	State Police/TSA Building	NA	NA	NA	NA	16.5	5.10	20.7	9.3
43	Boston EMS Station (Trailer)	NA	NA	NA	NA	16.48	0.88	20.67	5.07
43	Boston EMS Station (Garage)	NA	NA	NA	NA	16.48	3.83	20.67	8.02
44	North Gate	NA	NA	NA	NA	16.29	0.14	20.67	4.52
52	South Gate	NA	NA	NA	NA	16.08	NA	20.3	3.69
46	BOSFuel Operations and Control Bldg[2]	NA	NA	NA	NA	16.48	2.98	20.67	7.17
	Jet Fuel Tank Farm (Containment Wall)[1]	NA	NA	NA	NA	16.48	NA	20.67	3.46
32	Terminal A Satellite	NA	NA	NA	NA	16.19	NA	20.51	4.25
31	Terminal A Main (Airside)	NA	NA	NA	NA	16.19	NA	20.51	4.29
31	Terminal A Main (Landside)[1]	NA	NA	NA	NA	16.19	1.94	20.51	6.26
27	Terminal B (Pier A)	NA	NA	NA	NA	16.08	0.61	20.3	4.83
30	Terminal B (Pier B)	NA	NA	NA	NA	16.08	0.90	20.3	5.12
22	Terminal C (Main)	NA	NA	NA	NA	16.17	1.32	20.48	5.63
22	Terminal C (Pier C)	NA	NA	NA	NA	16.17	0.57	20.48	4.88
22	Terminal C (Pier B)	NA	NA	NA	NA	16.17	1.97	20.48	6.28
22	Terminal C (Pier A)	NA	NA	NA	NA	16.17	1.17	20.48	5.48
19	Terminal E	NA	NA	NA	NA	16.17	NA	20.63	3.65
19	Terminal E (Crawl space)	NA	NA	NA	NA	16.17	10	20.63	10
73	West Baggage Room	NA	NA	NA	NA	16.28	2.08	20.68	6.48
06B	Electrical/Telecom Building	NA	NA	NA	NA	16.49	3.32	20.67	7.5
06A	MPA Pumping Station (New)	NA	NA	NA	NA	16.49	5.42	20.67	9.6
	Water Shuttle Pier	NA	NA	12.31	NA	16.18	3.46	20.46	7.74
T18A	Tunnel T18A (utility hatch at West Garage)	NA	NA	NA	NA	16.18	NA	20.47	3.31
	Tunnel T18A (door at West Garage)	NA	NA	NA	NA	16.18	0.21	20.47	4.5
T18B	Tunnel T18B (utility hatch at West Garage)	NA	NA	NA	NA	16.18	NA	20.51	3.94
	Tunnel T18B (ventilation opening)	NA	NA	NA	NA	16.18	NA	20.51	X
T18C	Tunnel T18C (door at Central Garage)	NA	NA	NA	NA	16.17	1.52	20.47	5.82
	Tunnel T18C (ventilation at Old Tower)	NA	NA	NA	NA	16.18	X	20.48	X
	Tunnel T18C (hatch at Old Tower)	NA	NA	NA	NA	16.18	1.21	20.48	5.51
T18E	Tunnel T18E (door under overhead walkway to E)	NA	NA	NA	NA	16.17	2.5	20.63	6.96
T31A	Tunnel T31A (Stair LL)[1]	NA	NA	NA	NA	16.19	NA	20.47	4.21
T31B	Tunnel T31B (door at Term B airside)	NA	NA	NA	NA	16.08	1.26	20.31	5.49
66	Airfield Lighting Vault	NA	NA	NA	NA	15.98	0.56	20.3	4.88

Red = flooding above first floor projected under specified scenario
Green/NA = no flooding above first floor projected under specified scenario

Notes: Fields marked with an X indicate that first floor elevation was not available for that facility to estimate potential flood depth above first floor. Cat 1 MLW & MTL, and Cat 2 MLW do not show flooding above first floor for any facilities in Logan. Hence, these are not included in this table. All flood depths estimated based on survey elevations provided by Massport unless otherwise indicated by footnotes.

[1] Flood depth estimated based on elevation information in Record Drawings provided by Massport.
[2] Flood depth estimated based on LiDAR ground elevation data and field measurements.

Table 6b – Flood Elevations and Depths for Logan Airfield Electrical Sites

No.	Name	Flood Elevations (Elev) and Flood Depth Above First Floor (Depth)*							
		CAT 1 MHHW		CAT 2 MTL		CAT 2 MHHW		CAT 3 MHHW	
		Elev	Depth	Elev	Depth	Elev	Depth	Elev	Depth
		(ft NGVD29)	(ft)	(ft NGVD29)	(ft)	(ft NGVD29)	(ft)	(ft NGVD29)	(ft)
Airfield Electrical Sites (see below)									
	Site 1 - GS R/W 22L	NA	NA	NA	NA	15.87	3.08	20.23	7.44
	Site 2 - Vortac and R/W 33L ALS	NA	NA	NA	NA	15.35	3.58	19.25	7.48
	Site 3 - R/W 4R Glide Slope (GS)	NA	NA	NA	NA	15.75	2.9	19.72	6.87
	Site 4 - Fire Training (MPA)	NA	NA	NA	NA	15.56	NA	19.64	3.75
	Site 5 - ASR-9[2]	NA	NA	NA	NA	NA	NA	19.64	2.65
	Site 6 - RTR[2]	NA	NA	NA	NA	15.76	1.1	20.18	5.52
	Site 7 - R/W 4R ALS[2]	NA	NA	NA	NA	14.13	NA	19.64	5.3
	Site 8 - R/W 22L Localizer	NA	NA	NA	NA	15.66	0.09	19.87	4.3
	Site 9 - R/W 27 Localizer[2]	NA	NA	NA	NA	15.97	0.9	19.87	4.8
	Site 10 - R/W 4R Midpoint RVR[2]	NA	NA	11.81	0.01	15.76	3.96	19.92	8.12
	Site 11 - R/W 15R GS/PAPI/RVR	NA	NA	NA	NA	15.86	3.05	20.46	7.65
	Site 12 - R/W 15R MALS	NA	NA	NA	NA	16.17	3.03	20.58	7.44
	Site 13 - R/W 33L Localizer	NA	NA	NA	NA	16.17	NA	20.69	3.55
	Site 14 - R/W 22L MALSF	NA	NA	NA	NA	15.86	2.95	20.26	7.35
	Site 15 - Oil Water Separator (MPA)	NA	NA	NA	NA	16.17	2.28	20.58	6.69
	Site 27 - R/W 27 Glide Slope	11.15	NA	11.31	NA	15.35	2.07	18.99	5.71
	North Airfield Substation (MPA)[1]	NA	NA	NA	NA	16.77	0.37	20.77	4.37

Red = flooding above first floor projected under specified scenario
Green/NA = no flooding above first floor projected under specified scenario

Notes: Cat 1 MLW & MTL, and Cat 2 MLW do not show flooding above first floor for any facilities in Maritime South Boston. All flood depths estimated based on LiDAR ground elevation data and field measurements unless otherwise indicated by footnotes.

[1] Flood depth estimated based on survey elevation provided by Massport

Table 6c – Flood Elevations and Depths for Logan FAA Navigational Aids

Name	Flood Elevations and Flood Depths Above First Floor							
	CAT 1 MHHW		CAT 2 MTL		CAT 2 MHHW		CAT 3 MHHW	
	Elevation (ft NGVD29)	Depth (ft)	Elevation (ft NGVD29)	Depth (ft)	Elevation (ft NGVD29)	Depth (ft)	Elevation (ft NGVD29)	Depth (ft)
4R ALSF	11.36	NA	11.37	NA	15.77	2.29	19.37	5.89
4R Glide Slope	11.36	0.87	NA	NA	15.75	5.26	19.72	9.23
4R PAPI	NA	NA	NA	NA	15.76	3.53	19.72	7.49
4R Intermarker	NA	NA	NA	NA	15.77	NA	19.87	2.91
4R Localizer	NA	NA	NA	NA	NA	NA	20.62	2.37
22L MALSF	NA	NA	NA	NA	15.76	1.67	19.86	5.77
22L Glide Slope	NA	NA	NA	NA	15.86	4.32	20.23	8.69
22L PAPI	NA	NA	NA	NA	15.86	3.64	20.04	7.82
22L Localizer	NA	NA	NA	NA	15.76	0.61	19.86	4.71
15R MALSR	NA	NA	NA	NA	16.06	NA	20.57	3.31
15R Glide Slope	NA	NA	11.61	0.03	16.06	4.48	20.46	8.88
15R PAPI	NA	NA	NA	NA	15.86	3.09	20.46	7.69
15R Localizer	NA	NA	NA	NA	15.35	4.00	19.25	7.90
33L ALSF	11.15	NA	11.11	NA	15.24	2.43	18.92	6.11
33L Glide Slope	11.25	NA	11.31	NA	15.36	3.80	19.25	7.69
33L PAPI	NA	NA	NA	NA	15.35	2.75	19.25	6.65
22R PAPI	NA	NA	NA	NA	15.86	4.67	20.46	9.27
4L REIL (east)	NA	NA	NA	NA	15.87	2.69	20.08	6.90
4L REIL (west)	NA	NA	NA	NA	15.87	3.28	20.08	7.49
4L PAPI	NA	NA	NA	NA	15.87	4.88	20.19	9.20
27 REIL (north)	NA	NA	NA	NA	15.35	2.84	19.15	6.64
27 REIL (south)	NA	NA	NA	NA	15.15	3.31	19.15	7.31
27 Glide Slope	NA	NA	NA	NA	15.35	2.83	18.99	6.47
27 PAPI	NA	NA	NA	NA	15.36	2.72	19.25	6.61
27 Localizer	NA	NA	NA	NA	15.97	NA	20.30	3.16
32 REIL (north)	NA	NA	NA	NA	15.66	NA	19.64	2.89
32 REIL (south)	NA	NA	NA	NA	15.66	NA	19.64	2.26
32 PAPI	NA	NA	NA	NA	15.76	NA	19.86	3.41
Vortac	NA	NA	NA	NA	15.25	NA	18.99	0.10
ASR-9	NA	NA	NA	NA	15.66	NA	19.64	2.65
RTR (near 4R Glide Slope)	NA	NA	NA	NA	15.76	2.68	19.65	6.57
RTR (near 22L Glide Slope)	NA	NA	NA	NA	15.86	5.18	20.23	9.55
RTR/ Hygro-thermometer**	NA	NA	NA	NA	15.76	0.53	20.18	4.95

Red = flooding above ground projected under specified scenario
Green/NA = no flooding above ground projected under specified scenario

Notes: Cat 1 MLW & MTL, and Cat 2 MLW do not show flooding above first floor for any facilities in Maritime South Boston. All flood depths estimated based on LiDAR ground elevation data.

Table 7 – Flood Elevations and Depths for Maritime Facilities in South Boston

Facility	Name	Flood Elevations (Elev) and Flood Depth Above First Floor (Depth)							
		CAT 1 MHHW		CAT 2 MTL		CAT 2 MHHW		CAT 3 MHHW	
		NGVD	ft.	NGVD	ft.	NGVD	ft.	NGVD	ft.
Black Falcon	Berths[1]	NA	NA	12.1	NA	16.06	3.87	20.16	7.97
Black Falcon	Main Building	NA	NA	12.1	NA	16.06	2.29	20.16	6.39
Black Falcon	Gangway / FMT[1]	NA	NA	12.1	NA	16.06	3.87	20.16	7.97
Fish Pier	Berths[1]	11.46	1.64	12.33	2.51	16.06	6.24	20.15	10.33
Fish Pier	Fish Pier East Building (incl. Massport Police HQ)	11.57	0.82	12.24	1.49	16.28	5.53	19.65	9.71
Fish Pier	Transformer (adjacent to Guard House)[1]	11.57	1.35	12.34	2.12	16.27	6.05	20.41	10.19
Haul Road	Haul Road Sump Pump	NA	NA	NA	NA	NA	NA	20.55	11.11
Conley Terminal	Berth 11	11.39	0.22	11.93	0.76	15.96	4.79	19.93	8.76
Conley Terminal	Berth 12	11.35	0.09	11.36	0.1	15.86	4.60	19.94	8.68
Conley Terminal	Administration Building	11.35	NA	11.91	NA	15.85	3.59	19.81	7.55
Conley Terminal	Administration Building substation	NA	NA	NA	NA	15.86	3.33	19.76	7.23
Conley Terminal	Administration Building generator	1.68	NA	11.78	NA	15.75	2.63	19.75	6.63
Conley Terminal	Operations Building	na	NA	11.88	NA	15.76	3.29	19.76	7.29
Conley Terminal	Diesel Underground Storage Tank/ Fuel Island	na	NA	11.81	0.23	15.75	4.17	19.76	8.18
Conley Terminal	Gasoline Underground Storage Tank/ Fuel Island	11.36	NA	11.89	0.4	15.76	4.27	19.76	8.27
Conley Terminal	Massport Police Pro Shop Building	na	NA	11.89	NA	15.86	3.23	19.78	7.15
Conley Terminal	Gate Switch House	NA	NA	NA	NA	15.86	2.57	19.88	6.59
Conley Terminal	Site Switch House [1]	11.35	0.91	11.9	1.47	15.95	5.52	19.77	9.34
Conley Terminal	Wharf Switch Houses No. 1	11.46	NA	12.06	0.38	15.96	4.28	19.99	8.31
Conley Terminal	Wharf Switch Houses No. 2	11.46	0.22	12.12	0.88	15.96	4.72	20.07	8.83
Conley Terminal	Wharf Switch Houses No. 3	11.46	NA	12.12	NA	15.96	3.50	20.04	7.58
Conley Terminal	Vessel Crane 1	11.46	0.29	12	0.83	15.96	4.79	19.96	8.79
Conley Terminal	Vessel Crane 2	11.45	0.28	12.02	0.85	15.96	4.79	19.96	8.79
Conley Terminal	Vessel Crane 3	11.36	0.10	11.63	0.37	15.76	4.50	19.94	8.68
Conley Terminal	Vessel Crane 4	11.36	0.10	11.81	0.55	15.76	4.50	19.94	8.68
Conley Terminal	Vessel Crane 5	11.36	0.10	11.81	0.55	15.76	4.50	19.95	8.69
Conley Terminal	Vessel Crane 6	11.36	0.10	11.81	0.55	15.76	4.50	19.94	8.68
Conley Terminal	Rubber Tire Gantry Cranes[1]	11.36	0.36	12.01	1.01	15.95	4.95	19.77	8.77
Conley Terminal	Marine Operations Center	11.46	NA	12.01	0.26	15.96	4.21	19.96	8.21
Conley Terminal	Truck Processing Gate (Interchange Facility)[1]	11.35	1.75	11.91	2.31	15.85	6.25	19.75	10.15
Conley Terminal	Reefer Building	11.35	NA	11.63	NA	15.65	3.40	19.6	7.35
Conley Terminal	Reefer yard[1]	11.35	1.54	11.71	1.90	15.65	5.84	19.56	9.75
Conley Terminal	Reefer substation	11.36	NA	11.61	NA	15.66	3.20	19.55	7.09
Conley Terminal	Massport Police Main Gate Building (Guard House)	NA	NA	NA	NA	15.85	2.14	19.77	6.06
Other owners (non-MPA)									
Conley Terminal	MWRA Pump Station[1]	NA	NA	NA	NA	15.87	4.37	19.77	8.27
Conley Terminal	US Customs and Border Control Building	NA	NA	NA	NA	16.16	1.43	19.98	5.25

Red = flooding above first floor projected under specified scenario
Green/NA = no flooding above ground projected under specified scenario

Notes: Cat 1 MLW & MTL, and Cat 2 MLW do not show flooding above first floor for any facilities in Maritime South Boston. All flood depths estimated based on survey elevations provided by Massport unless otherwise indicated by footnotes.

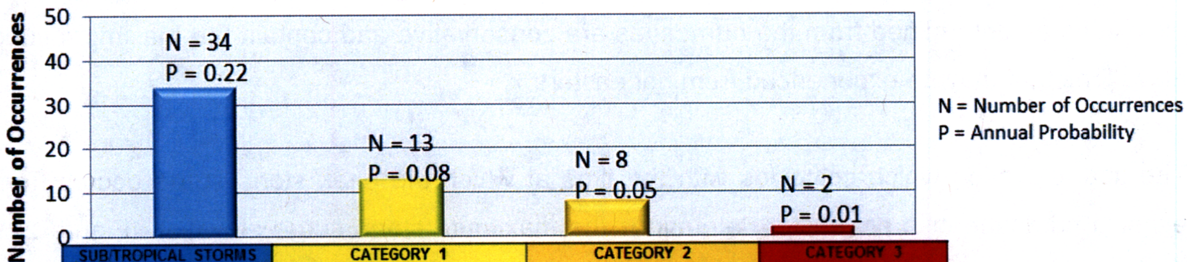
[1] Flood depth estimated based on LiDAR ground elevation data

For the critical buildings/facilities in Logan, the surge elevations associated with Category 2 and Category 3 hurricanes at MHHW vary between 14.13 – 16.79 ft NGVD29 and 18.92 – 20.78 ft NGVD29, respectively. For the critical maritime buildings/facilities in South Boston, the surge elevations associated with Category 2 and Category 3 hurricanes at MHHW vary between 15.65 – 16.28 ft NGVD29 and 19.55 – 20.55 ft NGVD29, respectively.

In consultation with the Massport executive committee, it was deemed appropriate to select separate design flood elevations for Logan and South Boston Maritime for retrofitting existing building/facilities and new construction. This decision was informed by the SLOSH modeling results that showed the maximum flood elevation at South Boston Maritime as being approximately 0.5 ft. lower than at Logan Airport. Therefore, for Logan Airport, 17.75 ft NGVD29 was selected as design flood elevation for retrofitting existing buildings/facilities and 21 ft NGVD29 as the design flood elevation for new construction. For maritime facilities in South Boston, 17.25 ft NGVD29 was selected as the design flood elevation for retrofitting existing buildings/facilities and 20.50 ft NGVD29 as the design flood elevation for new construction.

4.3 Historical Occurrence of Hurricanes in the Boston Harbor Region and Variability of Storm Types, Frequency and Tidal Elevation

Category 2 and Category 3 hurricanes were chosen as the base of design based on analysis of historic data, combined with the projected increase in storm frequency and intensity. Historical analysis of hurricane data revealed that, since 1858, Boston has been impacted by an estimated 23 hurricanes of varying intensities (See Figure 21). The most intense hurricanes to pass within 150 miles of Boston were two Category 3 hurricanes (recurrence interval 78 years) and eight Category 2 hurricanes (recurrence interval 20 years). Although their probability of occurring in any given year is low (approximately 1% annual chance for a Category 3, and 5% annual chance for a Category 2), it is reasonable to estimate the maximum possible flood elevations associated with these events at Logan and maritime facilities in South Boston. Again, it is important to note that SLOSH MOM simulations for Category 2 and Category 3 hurricanes were used to determine the design flood elevations assuming hurricane occurs at MHHW and considered the worst-possible combination of hurricane parameters, including landfall location, forward speed, hurricane track direction, radius to maximum winds and central pressure.



SUBTROPICAL STORMS & DEPRESSIONS	CATEGORY 1 HURRICANE	CATEGORY 2 HURRICANES	CATEGORY 3 HURRICANES
	Hurricane Sandy [1]: October 29-30, 2012	**Hurricane Bob:** August 16 - 29, 1991	**Hurricane Esther:** September 10 - 27, 1961
	Great Atlantic Hurricane of 1944: September 9 - 16, 1944	**Hurricane Gloria:** September 27, 1985	**Hurricane of 1869:** September 7 – 9, 1869
	Unnamed (1936): September 8 - 25, 1936	**Hurricane Donna:** September 12, 1960	
	Unnamed (1924): September 27 - 30, 1924	**Hurricane Edna:** September 11, 1954	
	Hurricane of 1916: July 10 - 22, 1916	**Hurricane Carol:** August 31, 1954	
	Unnamed (1904): September 8 - 15, 1904	**Great New England Hurricane:** September 21, 1938	
	Unnamed (1896): August 30 - September 11, 1896	**Unnamed (1924):** August 16 - 28, 1924	
	Unnamed (1894): October 1 - 12, 1894	**Unnamed (1869):** October 4 - 5, 1869	
	Unnamed (1893): August 15 - 26, 1893		
	Unnamed (1888): September 23 - 27, 1888		
	Unnamed (1885): September 17 - 23, 1885		
	Unnamed (1879): August 13 - 20, 1879		
	Unnamed (1858): September 14 - 17, 1858		

[1] All storms listed above tracked within 150 miles of Boston, except Hurricane Sandy.

Figure 21 – Historical Occurrence of Hurricanes in Boston from 1858-2013

Other than hurricanes, the maximum storm surge associated with extratropical storms, such as nor'easters were also evaluated. A discussion of storm surge associated with nor'easters has been included in Section 3.2.2. Based on historical data, the highest storm surge from a nor'easter experienced in the Boston Harbor region since 1952 was 6.19 ft on February 26, 2010. Since the peak surge did not occur at high tide, the storm surge elevation experienced was lower. If this peak were to coincide with the mean higher high tide (5.58 ft NGVD29), the maximum storm tidal elevation could have reached 11.77 ft NGVD29 for the February 2010 nor'easter. However, this maximum surge elevation is well within the maximum surge elevation associated with the Category 2 and 3 hurricanes. Similarly, the maximum water surface elevation that was recorded at the Boston Harbor tidal gage during the blizzard of 1978 was 10.33 ft NGVD29, which is also within the maximum surge elevation associated with the Category 2 and 3 hurricanes. Hence, even though nor'easters may cause greater damage to

infrastructure since they have a larger fetch and last for longer tidal cycles, the design flood elevations as determined from the hurricanes are conservative and contain the maximum flood elevations that may be experienced from nor'easters.

The tidal elevation which coincides with the time at which the peak storm surge occurs from either a hurricane or a nor'easter determines the maximum storm surge elevation (Figure 22). The two tidal elevations that were evaluated were the mean higher high water (MHHW) and the highest astronomical tide (HAT). The MHHW is the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch (the current tidal datum epoch 1983-2001 was considered for this study), which is 5.58 ft NVVD29 for the NOAA Boston Harbor tidal station (NOAA tidal station 8443970). The HAT is the elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the National Tidal Datum Epoch, which is 7.73 ft NGVD29 for the NOAA station 8443970. Figure 23 presents the number of historical hurricanes since 1921 that have occurred at the different tidal elevations. It is observed from this figure that historically no Category 2 or 3 hurricanes have occurred at HAT or MHHW. However, since two Category 2 hurricanes have occurred at MHW in the Boston Harbor area, and Hurricane Sandy made landfall at Atlantic City as a Category 1 hurricane at MHHW, the scenario of a Category 2 or 3 hurricane making landfall at MHHW in Boston was selected as the worst-possible hurricane landfall scenario. Hence it was deemed appropriate to consider the MHHW tidal elevation in the SLOSH simulations for determining the design flood elevation for Massport Logan and South Boston Maritime properties.

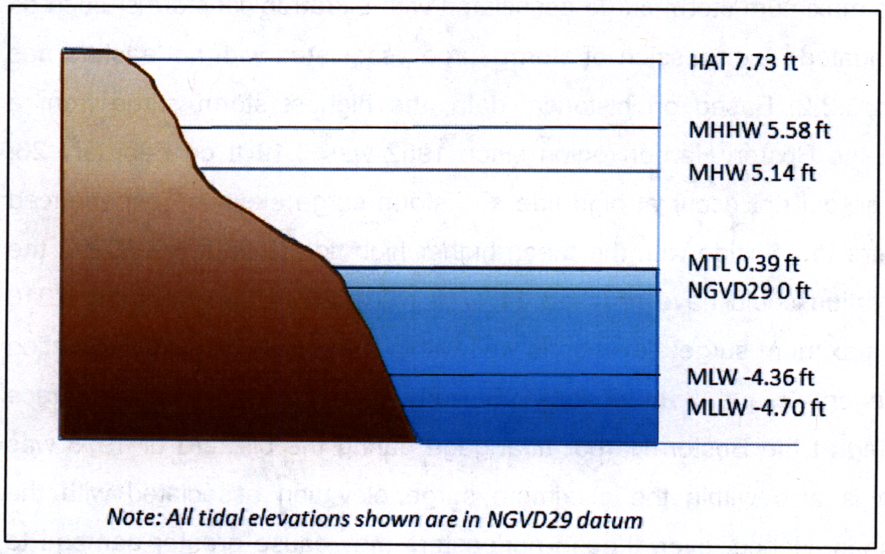
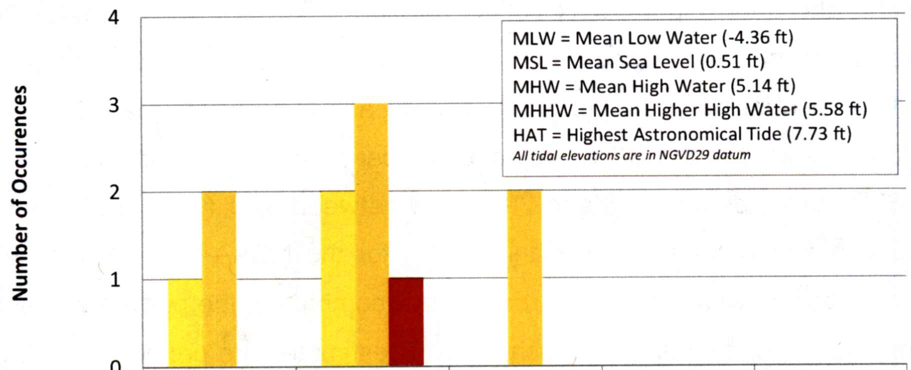


Figure 22 – Boston Harbor Tidal Elevation Datums (NTDE 1983-2001)



	MLW	MSL	MHW	MHHW	HAT
Category 1	1	2	0	0	0
Category 2	2	3	2	0	0
Category 3	0	1	0	0	0

Sandy made final landfall near Atlantic City, NJ on 10/30/2012 00:00 GMT as a Category 1 hurricane at MHW (NOAA, 2013)

Figure 23 – Historical Occurrence of Hurricanes Since 1921 in Boston at Different Tidal Conditions

4.4 Sea Level Rise and Storm Intensification Considerations

The design flood elevation selected for Logan Airport and maritime facilities in South Boston also considered future sea level rise considerations and possible increase in frequency of more intense hurricanes in the Atlantic (Bender et al. 2010). According to the paper by Bender et al., the influence of global warming on Atlantic hurricanes based on using downscaled global climate models and an operational hurricane prediction model showed an increase of 40% (using the GFDL climate model) in the frequency of major hurricanes (Category 3-5). The study also concluded that the model projects nearly a doubling of the frequency of Category 4 and 5 hurricanes by the end of the 21st century, despite a decrease in the overall frequency of tropical cyclones. Since the frequency of major hurricanes (Category 3 - 5) are projected to occur more frequently in the Atlantic as result of climate change, it was deemed appropriate to select the Category 2 hurricane for retrofitting existing buildings/facilities and Category 3 hurricanes for construction of new buildings which will have a longer expected service life.

A detailed description of sea level rise projections has been included in Section, 3 Climate Analysis – Past Events and Future Trends. For the purposes of selecting design elevations, the NOAA/NCA "intermediate-high" sea level rise (SLR) scenario was evaluated in addition to the NOAA/NCA "highest" SLR scenario.

Table 8 below presents the total relative SLR values (global SLR according to NOAA 2012 scenarios, with an assumed land subsidence rate of 0.04 in./yr) for the years 2020 through 2100 in 10 year increments. It also includes the years 2033, 2043 and 2053 which mark 20, 30, 40 years, respectively from the start of the DIRP project study period in 2013. It can be observed from this table that SLR estimates for 2033 and 2043 vary between 0.81 ft and 1.37 ft for the NOAA "Highest" scenario and between 0.53 ft and 0.88 ft for the NOAA "Intermediate-High" scenario. Based on discussions with the Massport executive committee, the preferred scenario is the NOAA "Intermediate-High" scenario, in which the SLR estimates are projected to be less than 1 ft though 2043. Also, since 2043 represents approximately 30 years from the present, and most building retrofits have a design life of 20-30 years, the SLR considerations upto 2043 seem appropriate. The sea level rise value is a small fraction compared to the worst-possible storm surge elevations that have been considered. Therefore, this rise is accommodated within the proposed DFEs; and no additional adjustments were made for sea level rise in the design flood elevations.

Table 8 – Scenario Projections for Total Relative SLR in Boston (2020-2100)[1,2,3]

Scenarios	2020	2030	2033	2040	2043	2050	2053	2060	2070	2080	2090	2100
"Highest" (ft.)	0.24	0.66	0.81	1.19	1.37	1.82	2.03	2.56	3.39	4.33	5.37	6.52
"Intermediate-High" (ft.)	0.16	0.44	0.53	0.77	0.88	1.16	1.29	1.61	2.12	2.68	3.30	3.98
"Intermediate-Low" (ft.)	0.09	0.24	0.29	0.40	0.46	0.59	0.65	0.79	1.01	1.24	1.50	1.77

[1] Total Relative SLR is calculated here as the sum of Global SLR and local land subsidence. The base year is 2013.

[2] Scenarios of Global SLR are from the 2012 NOAA Technical Report on Global Sea Level Rise Scenarios for the United States National Climate Assessment, December 2012.

[3] Land subsidence in Boston is estimated to be 0.04 in/yr for the purposes of this assessment.

4.5 Flood Elevations Proposed by FEMA

The maximum storm surge elevations from Category 2 and 3 hurricanes were also compared with the existing 2009 FEMA and the proposed 2013 FEMA flood elevations as illustrated in Figures 9 and 10. The maximum 2009 FEMA 100-yr base flood elevation among the Logan critical facilities is 10.81 ft NGVD29 (for AE zone) and 13.81 ft NGVD29 (for VE zone), while the proposed maximum 2013 FEMA AE zone and VE zone (velocity zone with wave action)

elevations are 12.81 ft NGVD29 and 14.81 ft NGVD29, respectively. The 100-yr elevations are defined as the elevations that have a 1% annual chance of exceedance without significant wave action (for AE zone) and with significant wave action (for VE zone). Also, as discussed with the Massport executive committee on April 30, 2014, the FEMA 500-yr flood elevations for Massport facilities were also considered (11.91 ft NGVD29 for Logan and 12.31 ft NGVD29 for South Boston maritime). The 500-yr elevation is defined as the flood elevation that has a 0.2% annual chance of exceedance. For the 500-yr flood elevation, FEMA only reports the flood elevation with no significant wave action. However, the higher wave setup value of 3 ft from the 100-yr flood elevations was added to the FEMA 500-yr flood elevation and 14.91 ft NGVD29 and 15.31 ft NGVD29 were reported as the potential 500-yr flood elevations with wave action added for Logan and South Boston maritime respectively. Since these flood elevations were still within the Category 2 and 3 flood elevations using the SLOSH MOM simulations for Massport's Logan Airport and maritime facilities in South Boston, the choice of design flood elevation of 17.75 ft NGVD29 (for Logan Airport) and 17.25 ft NGVD29 (for maritime facilities in South Boston), for retrofitting existing buildings and 20.78 ft NGVD29 (for Logan Airport and 20.50 ft NGVD29 (for maritime facilities in South Boston) for new buildings was deemed appropriate.

4.6 Further Comparison with other Regional Studies

The methodology for developing inundation extents used in this study relies on a scenario-based approach. The flooding extent is associated with a particular event, such as a Category 1 hurricane or a nor'easter. Flooding extents can also be analyzed from the perspective of probability – in other words, what is the probability that the area will be flooded on a yearly basis, irrespective of the particular event which is causing it? This is the approach that is currently being used by the Woods Hole Group for the their study with the MassDOT which focuses on the vulnerability of the Central Artery system in Boston. The model being developed, the Boston Harbor Risk Model (BH-FRM), is comprised of the Advanced CIRCulation model (ADCIRC), a two-dimensional, depth-integrated, long wave, hydrodynamic model in combination with the Simulating WAves Nearshore model (SWAN), a wave generation and transformation model. This model is being developed using a probability-based approach with a fully-optimized Monte Carlo approach. The results from this model will be available as exceedance probability of combined sea level rise and storm surge. It would be useful for Massport to be familiar with the results of this study and think about what information may be incorporated to further hone the areas of focuse with respect to resiliency investment. However, given the difference

between the two approaches – probability versus scenario-based - there a standardized reporting mechanism will need to be developed to allow for comparison and evaluation between the two.

7. CONCLUSION

Climate change is redefining risk within the built environment as historic events can no longer reliably predict future conditions. This creates an extremely challenging environment for infrastructure owners and operators, such as Massport, to adapt. By commissioning this study, Massport has taken a proactive stance and developed a resiliency plan to ensure business continuity in the midst of an uncertain future.

Approximately $50 million in resiliency improvements were identified through this project. The study focused primarily on coastal flooding associated with sea level rise and storm surge, and, to a limited extent, operational aspects. The recommended investments included both wet and dry flood-proofing methods, with a focus on rapid recovery following the event. High levels of flood protection were recommended for the most critical infrastructure, such as electrical distribution, emergency response, and aviation safety facilities. Where appropriate, in light of the limited available resources, operational alternatives to capital investments, and lower consequences of failure, some infrastructure was not recommended for full or even partial floodproofing. Recommendations were also prioritized considering elements of risk, including probability and consequence of flood-induced failure.

The resiliency recommendations listed within this report are informed by the scenario-based simulation of selected climate change parameters for Massport, and informed by the understanding of asset criticality and climate science at the time of writing this report. The Resiliency Plan should be considered a dynamic document to inform planning priorities based on the latest information available from scientific modeling, collaboration with key stakeholders and subject matter experts, other regional and national initiatives and the overall impact of all those factors on Massport's various business lines. The results of this work provide a framework for near term action and future updates as Massport works to integrate resiliency into its infrastructure and operations over the long term.

8. REFERENCES

Emanuel, K. (2013). Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity over the 21st Century, PNAS, Early Edition, Accepted June 10, 2013.

Intergovernmental Panel on Climate Change (IPCC) (2012). Managing the Risks of Extreme Events and Disaster to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the IPCC.

Intergovernmental Panel on Climate Change (IPCC) (2013). Working Group I, Summary for Policy Makers.

Kirshen, P.H., Knee, K., Ruth, M. (2008). Adaptation to Sea Level Rise in Metro Boston, Climatic Change, 90(4), pages 453-473.

Knutson, T., Sirutis, J., Vecchi, G., Garner, S., Zhao, M., Kim, H-S., Bender, M., Tuleya, R., Held, I., and Villarini, G. (2012) Dynamic Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios, Climate, 1 September 2013.

Moser, S., Davidson, M., Kirshen, P., Mulvaney, P., Murley, J., Neumann, J., Petes, L., and Reed, D. (2012) Coastal Zone Development and Ecosystems, Draft, Chapter 25 of the US National Climate Assessment 2013 Report, US Global Change Research Program, Washington DC, July 2, 2012.

National Oceanic and Atmospheric Administration (NOAA) (2012). Global Sea Level Rise Scenarios for the United States National Climate Assessment. Available online at: http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf

National Oceanic and Atmospheric Administration (NOAA) (2013). Updated Mean Sea Level Trends – 8443970 Boston, Massachusetts. Available online at: http://tidesandcurrents.noaa.gov/sltrends/sltrends_update.shtml?stnid=8443970

Pryor, S.C., R.J. Barthelmie, and E.S. Riley, (2007). Historical evolution of wind climates in the USA. Journal of Physics: Conference Series, 75, 012065.

Pryor, S. C., R. J. Barthelmie, D. T. Young, E. S. Takle, R. W. Arritt, D. Flory, W. J. Gutowski Jr., A. Nunes, and J. Roads (2009). Wind speed trends over the contiguous United States, J. Geophys. Res., 114, DOI: 10.1029/2008JD011416.

Pryor, S. C., and J. Ledolter (2010). Addendum to “Wind speed trends over the contiguous United States”, J. Geophys. Res., 115, DOI: 10.1029/2009JD013281.

World Meteorological Organization (WMO) (2010). Guidelines for Converting Between Various Wind Averaging Periods in Tropical Cyclone Conditions.